Monitoring Subsidence at the Lost Hills Diatomite Oil Field, California

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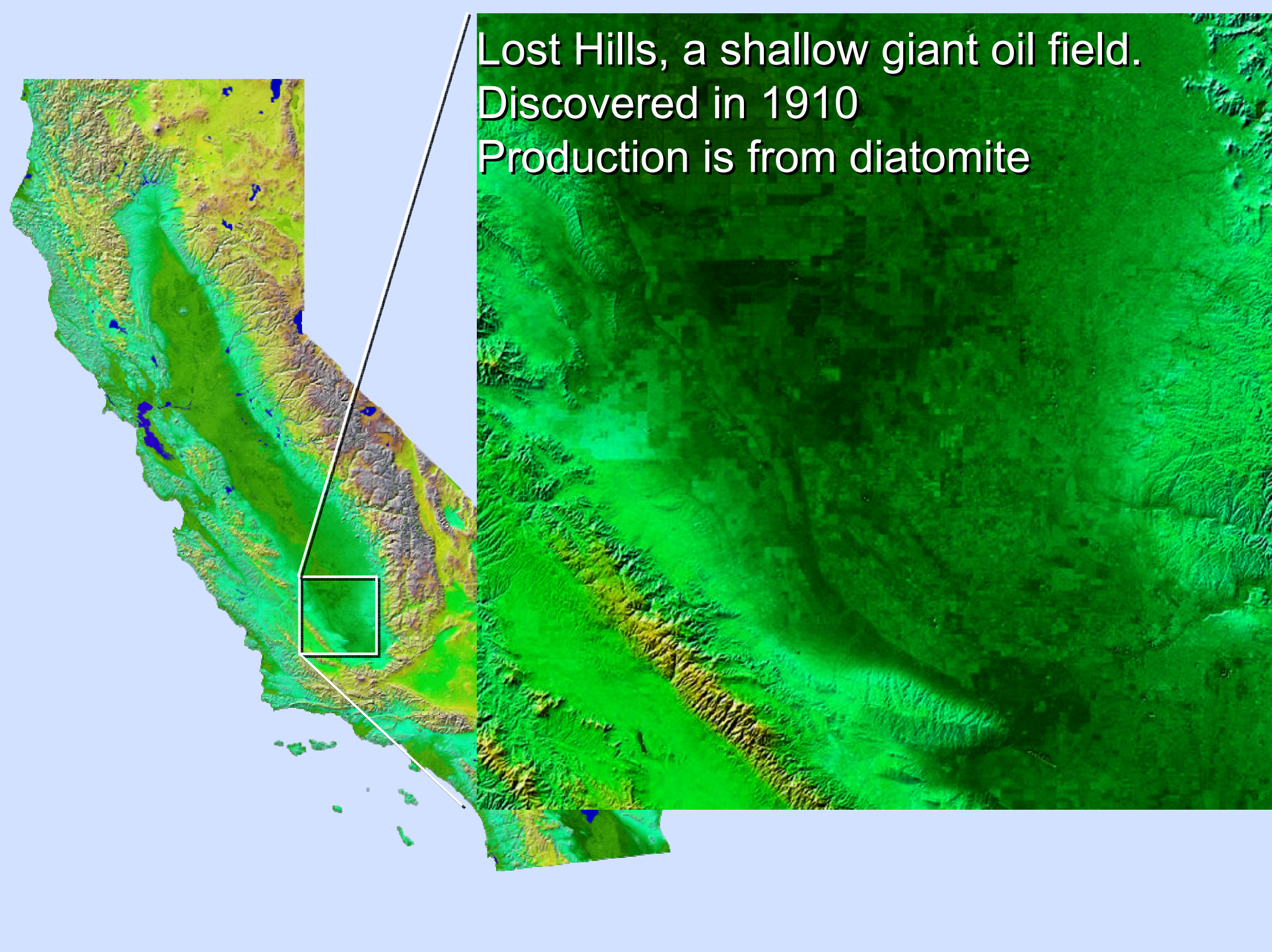
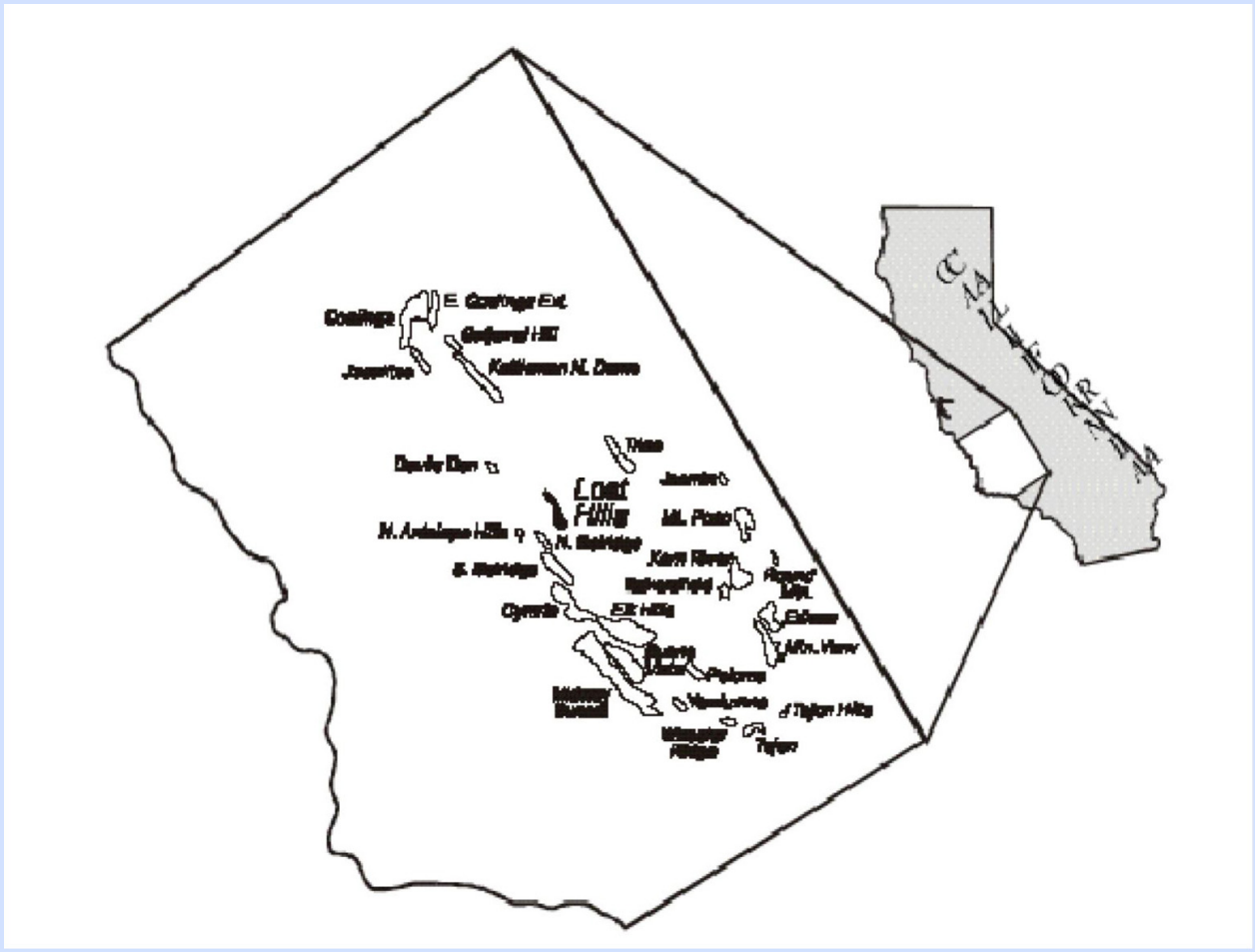
Lawrence Berkeley National Lab

Sponsors: NASA Earth Science Applications
UC Berkeley Oil Consortium
Chevron
WinSAR
Alaska Satellite Facility


Lost Hills, a shallow giant oil field.
Discovered in 1910
Production is from diatomite



Lost Hills is one of many Miocene oil fields in Central California
10 billion barrel oil field, comparable in volume to Prudhoe Bay
High porosity, low permeability, so production encouraged by hydrofracing
Water injection to control subsidence and fracture rocks
Coupled modeling of InSAR, GPS, and injection data shows unexpected behavior
Developing model used to manage the wells and production

Subsidence affects wells and other infrastructure

Damage has been as high as $1M/yr

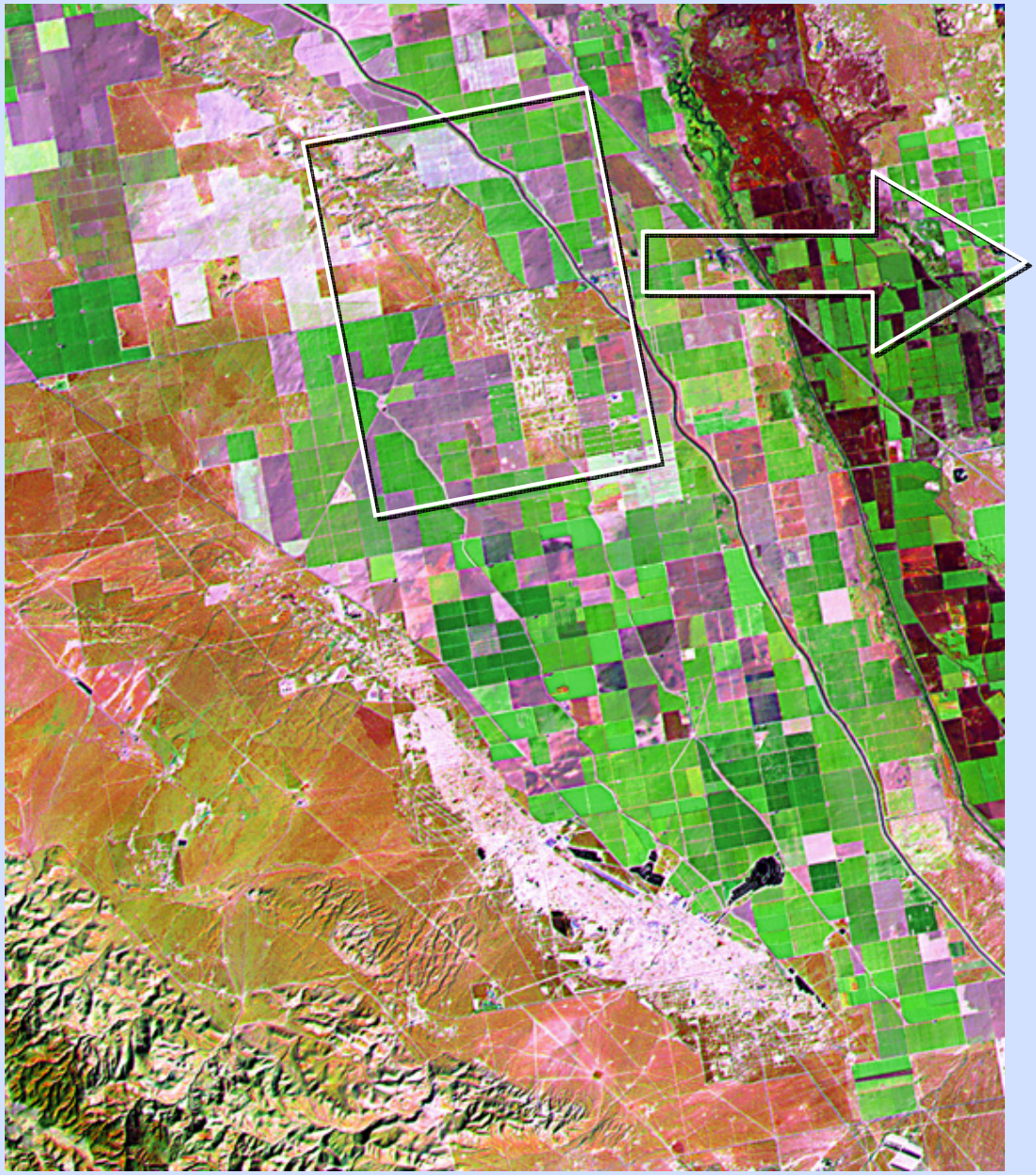
Production is ~$1M/day

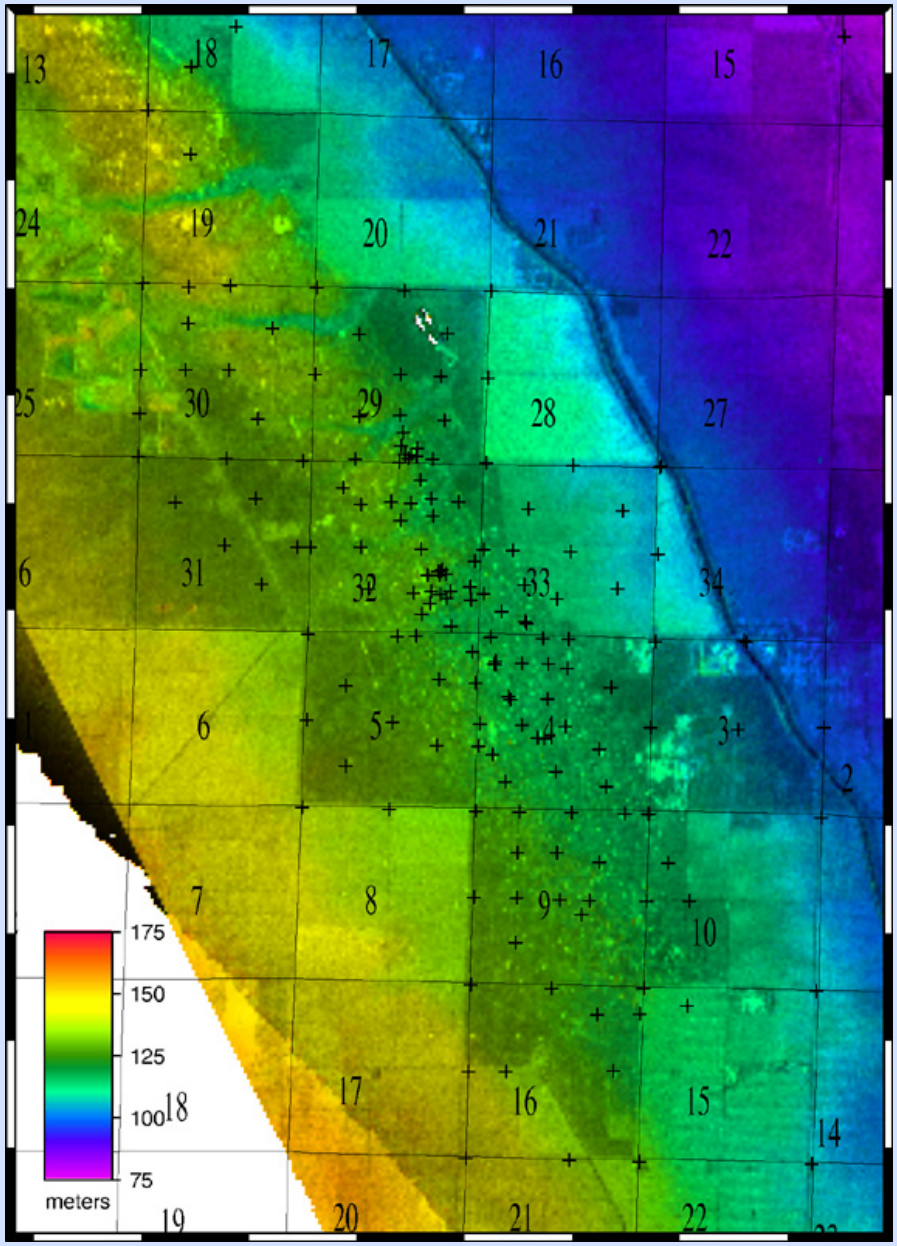
How to measure subsidence?

Surveying, GPS, DEMs from airborne LIDAR, TopSAR, or satellite InSAR

Landsat TM 542

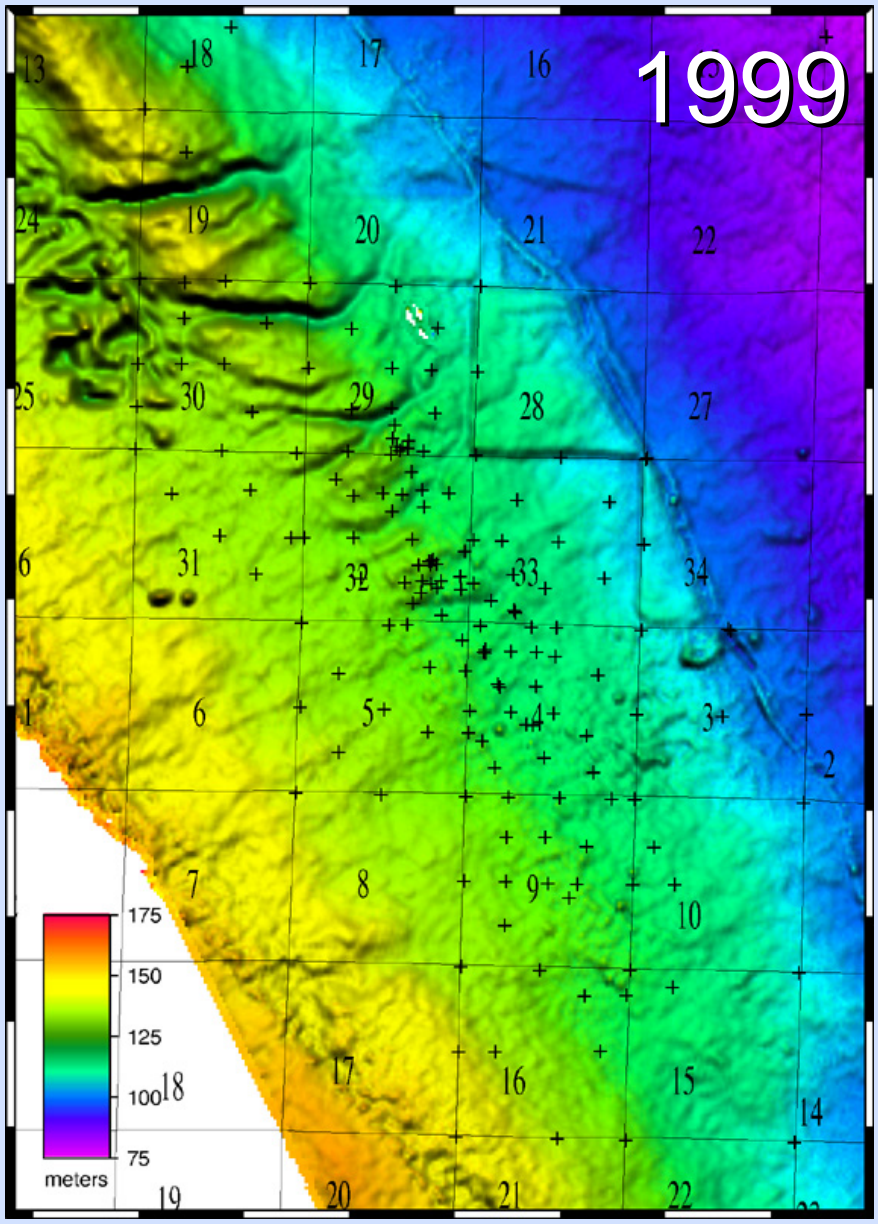
TopSAR 1999 Elevation & Image

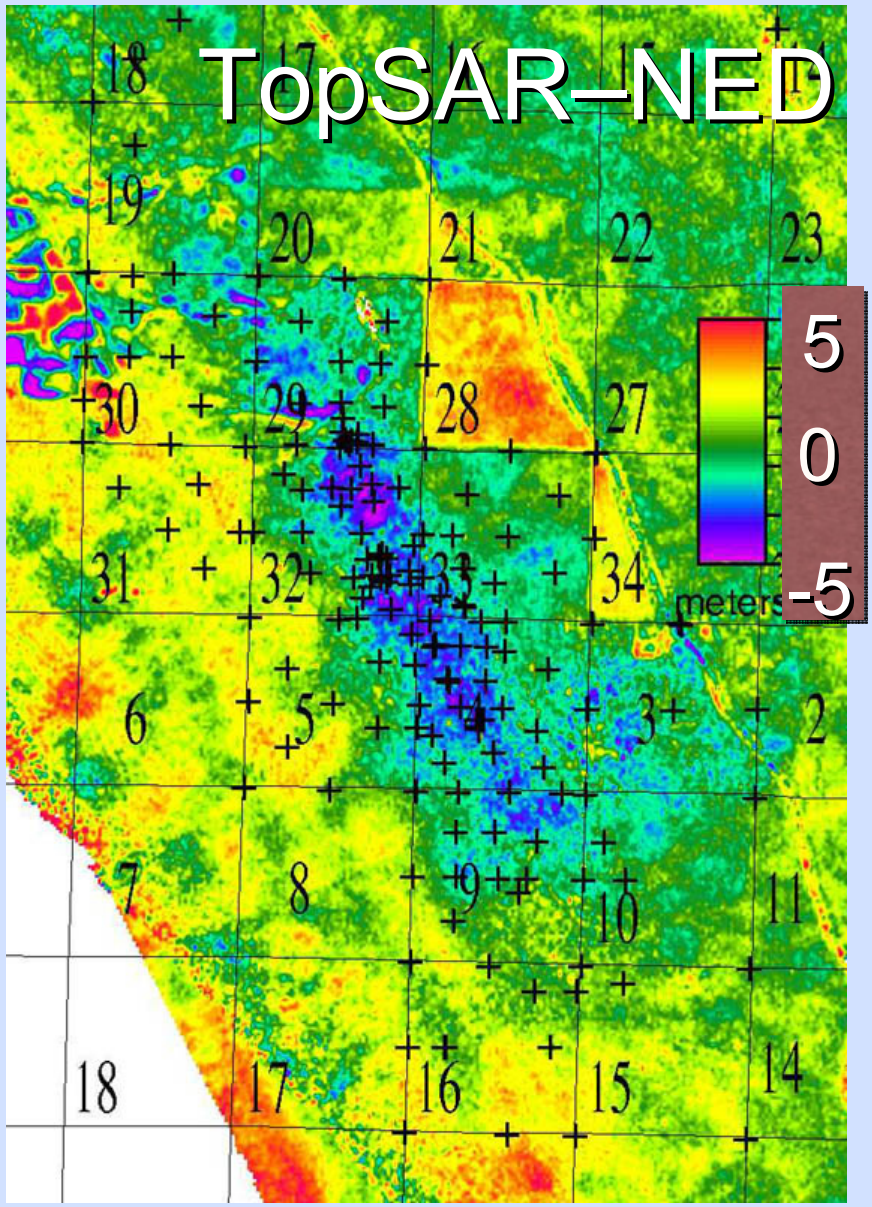




TopSAR is topo mapping mode for AirSAR, 5m postings, ~2m Z

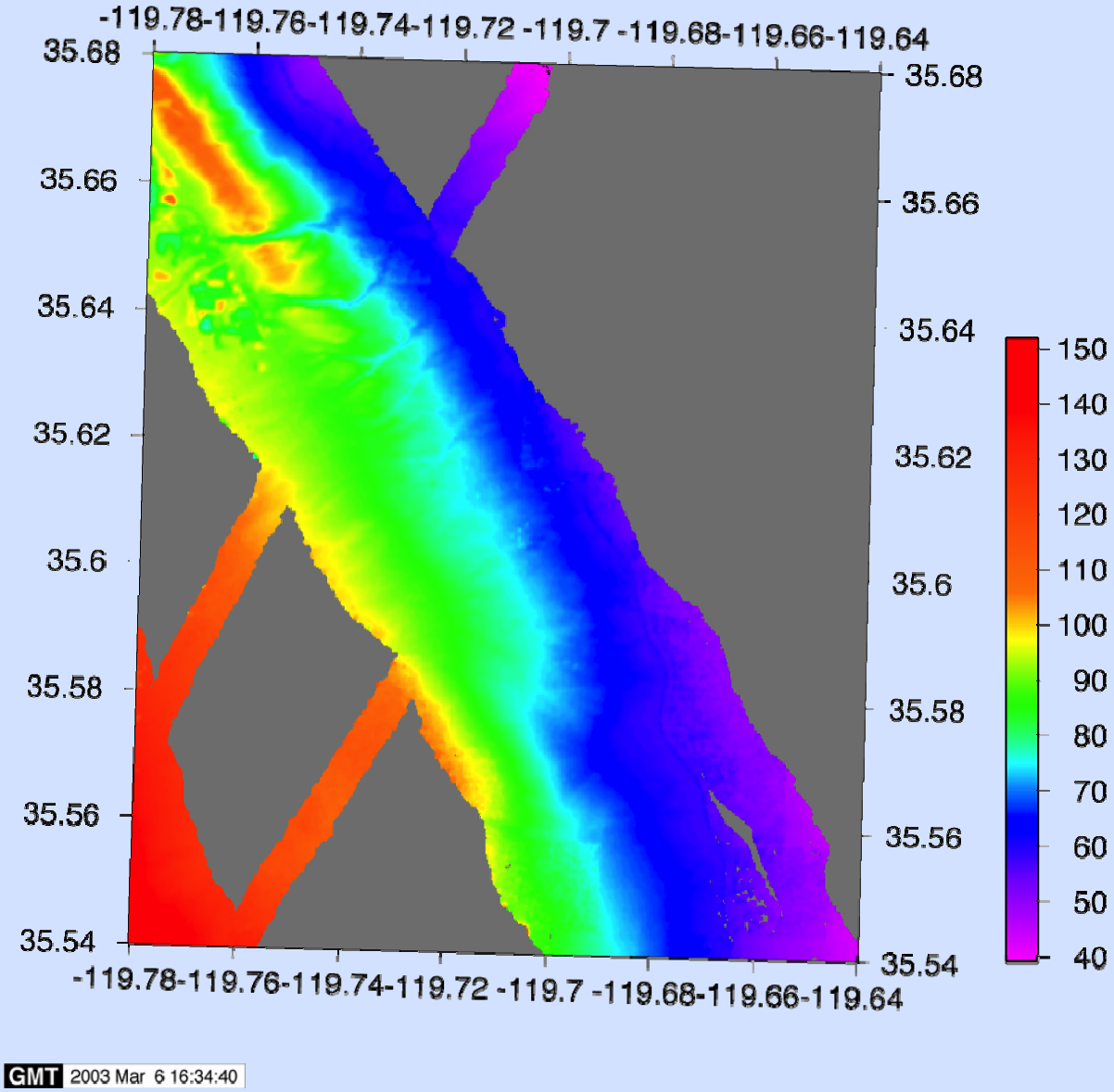
Elevation Change 1982-1999



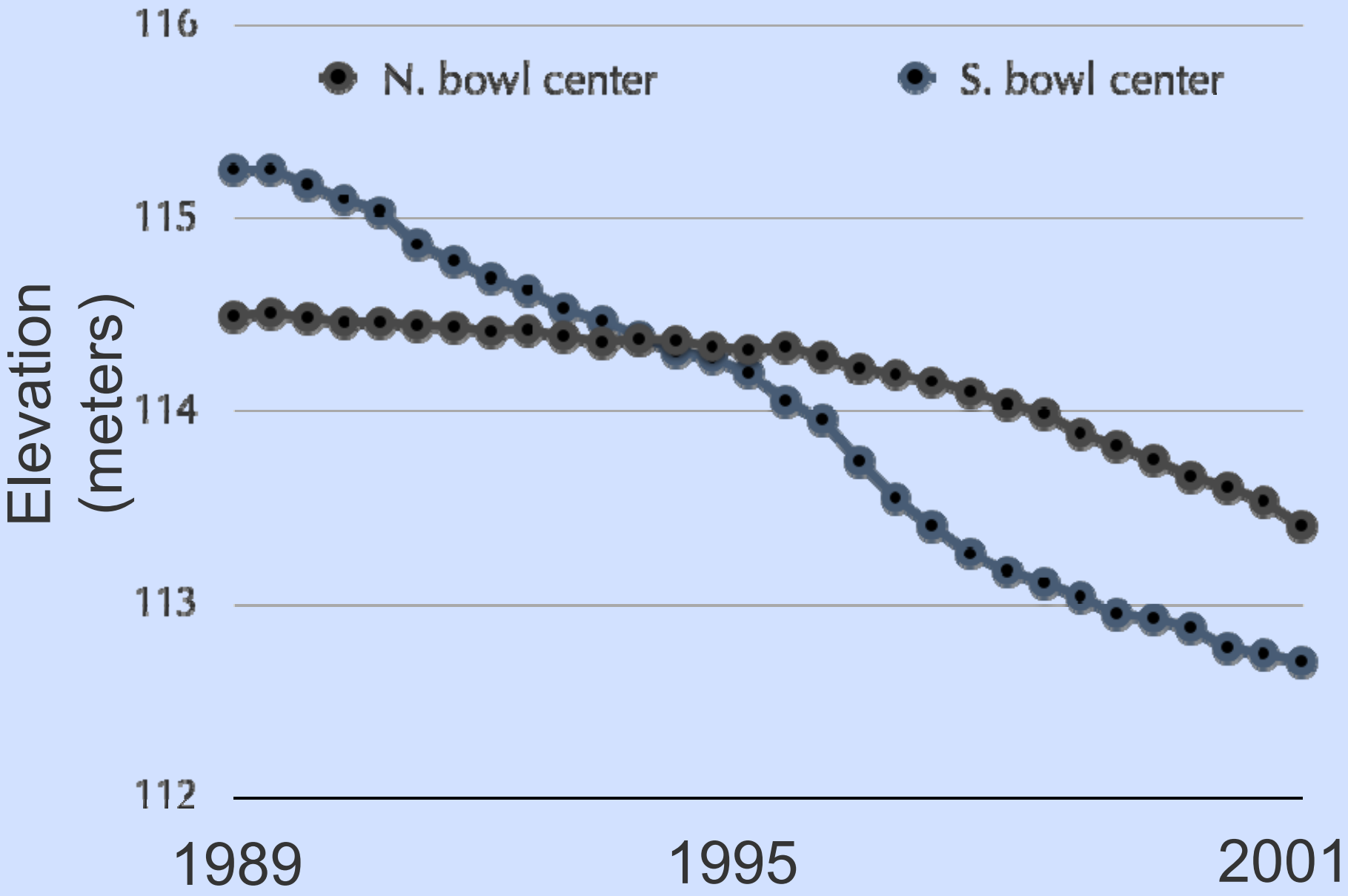


Airborne LiDAR altimetry

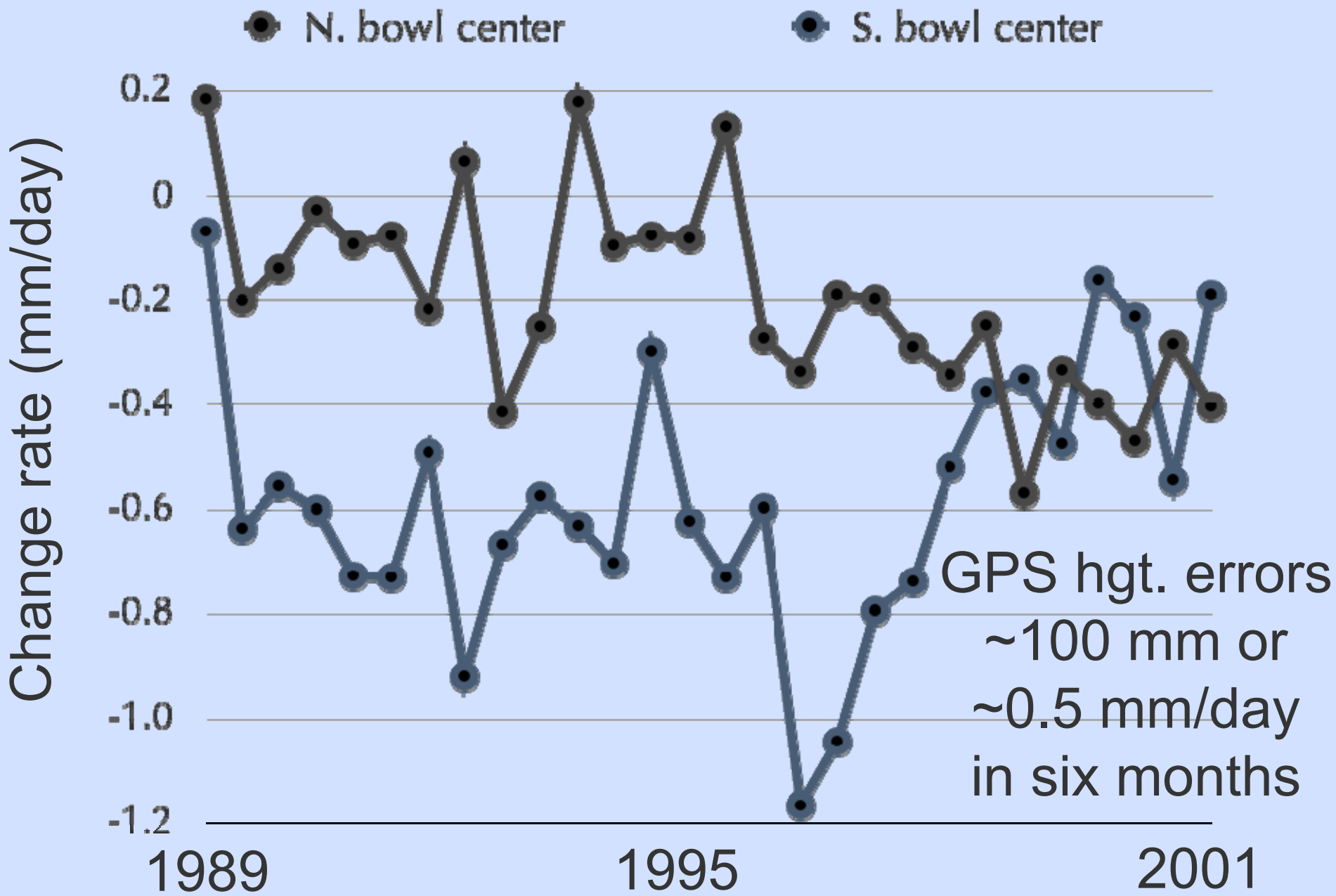
- Wallops ATM
- flown Sept. 2002
- estimated 10 cm vertical accuracy
- swath about 400 m wide
- roughly 1 meter spacing
- not yet filtered to retrieve “bare earth” elevations



GPS stations surveyed twice a year



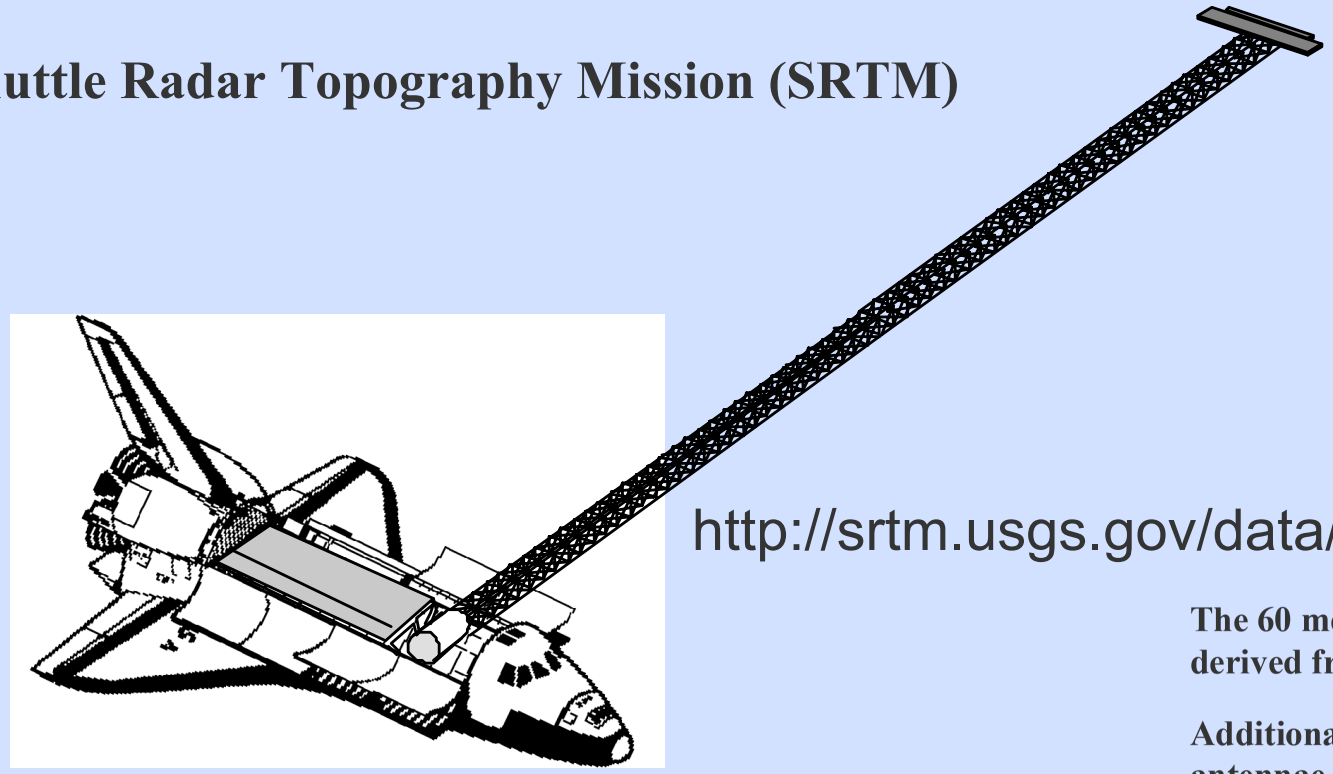
GPS elevation change rates



Applications of Radar Interferometry-InSAR

- Interferometric SAR concept-2 or more SAR observations of the surface.
- Use the same, or identical, sensor systems (e.g. ERS 1,2, EnviSAT, RadarSAT).
- Observation geometry must be very tightly constrained and known.
- Phase differences between two observations yield topography.
- Phase differences when topography is known, either from topographic data or from multiple InSAR observations over time yield **topographic change.**
- Errors from ionosphere, atmospheric water vapor……
- Deccorelation-surface change such as veg growth can prevent generation of interferograms-decorrelation is wavelength dependent.
- Presently available InSAR capable satellites were not designed for InSAR and are subject to the difficulties above.
- A proposed (repeatedly) dual frequency L-Band InSAR would largely overcome these problems.
- When everything works, you get a geographically comprehensive map of surface displacement which occurred between your observations.

The Shuttle Radar Topography Mission (SRTM)



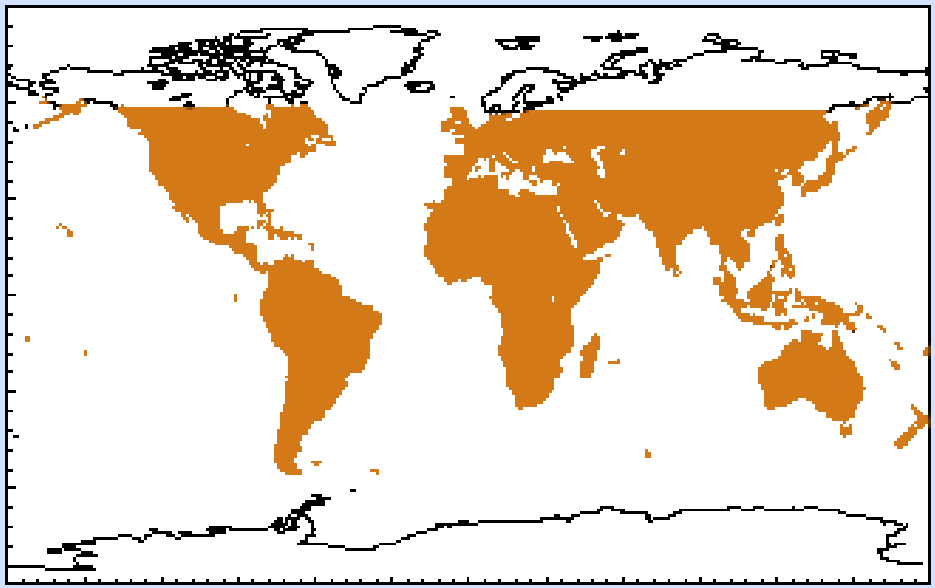
http://srtm.usgs.gov/data/obtainingdata.html

The 60 meter long deployable mast is derived from Space Station hardware.

Additional C-band and X-band antennae are located at the end of the mast.

Avionics are added for attitude and orbit determination.

The X-band interferometer is supplied by the German and Italian space agencies.



The shaded area was mapped by SRTM.

SRTM acquired data with 225 km swaths for ten days, imaging all of the Earth's land surface between 60° N and 56° S latitude.

Data processed into a digital topographic map. SRTM will also produce a rectified, terrain-corrected C-band image mosaic of 80% of the Earth's land surface at 30 meter resolution.

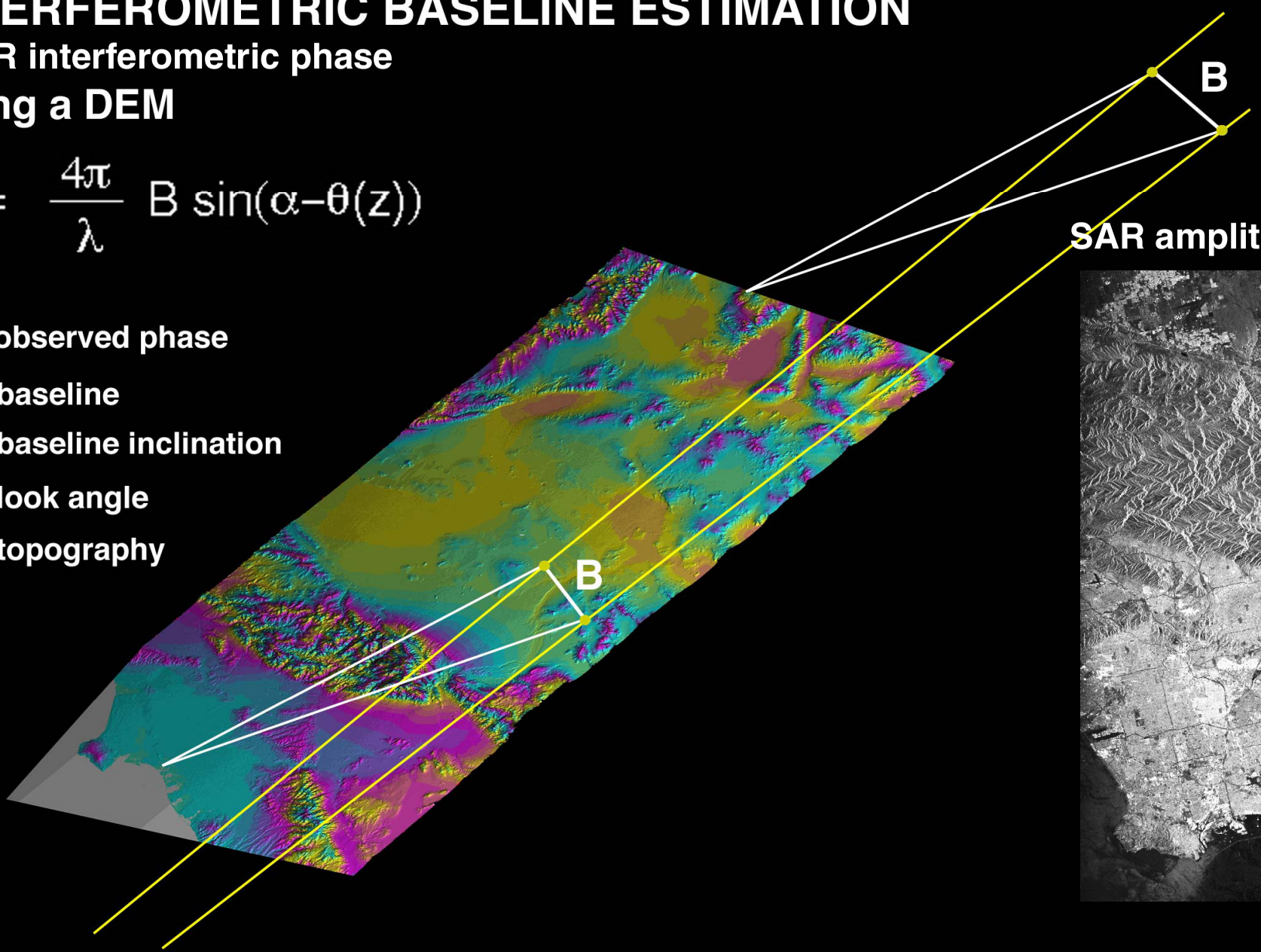
Synthetic Aperture Radar Interferometry (InSAR)
A geodetic imager

INTERFEROMETRIC BASELINE ESTIMATION

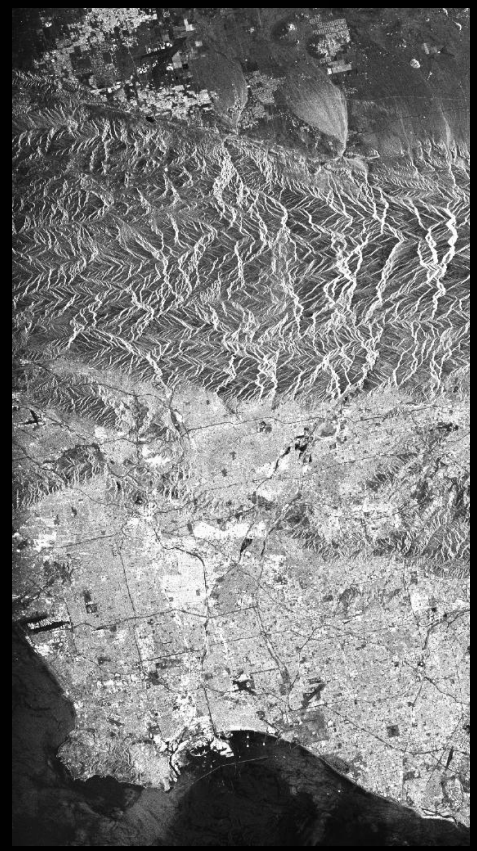
SAR interferometric phase
using a DEM

$$\Phi = \frac{4\pi}{\lambda} B \sin(\alpha - \theta(z))$$

- Φ observed phase
- B baseline
- α baseline inclination
- θ look angle
- z topography

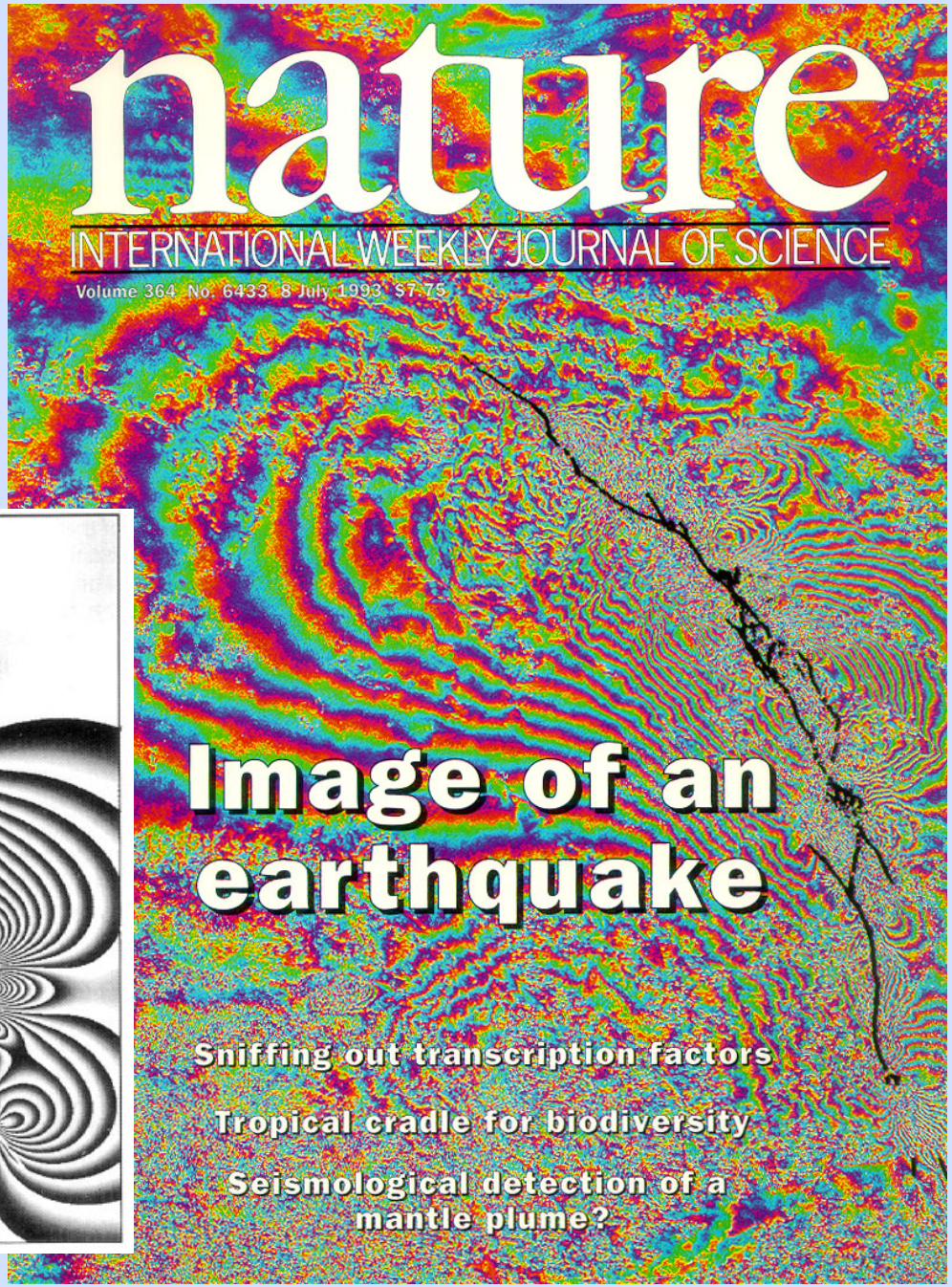


SAR amplitude image

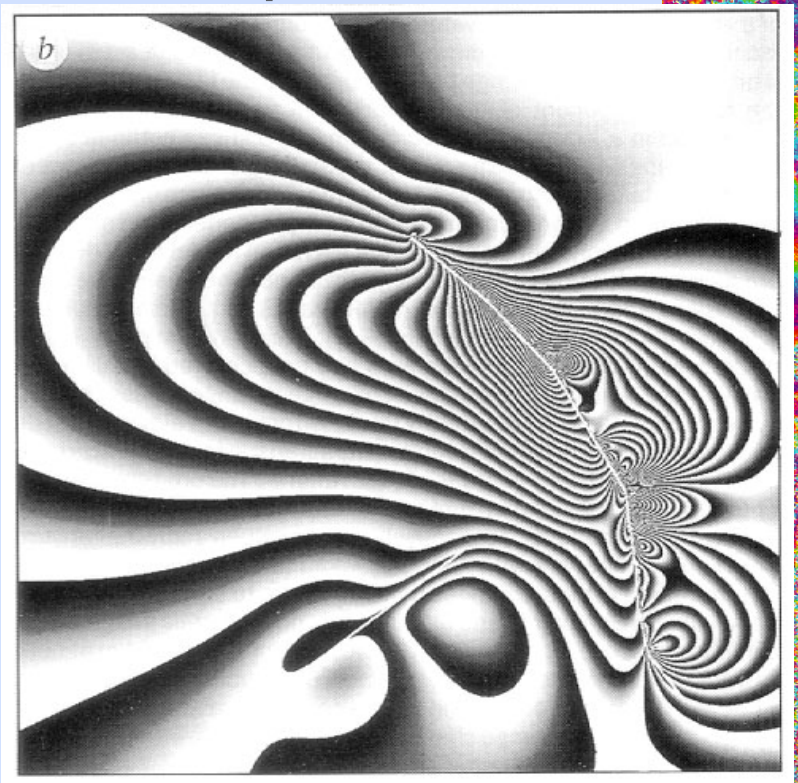


It is with the images of ERS acquired before and after the Landers 1992 earthquake that the first interferogram of an earthquake was produced.

Observed phase


nature
INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
Volume 364 No. 6433 8 July 1993 $7.75
Image of an earthquake
Sniffing out transcription factors
Tropical cradle for biodiversity
Seismological detection of a mantle plume?

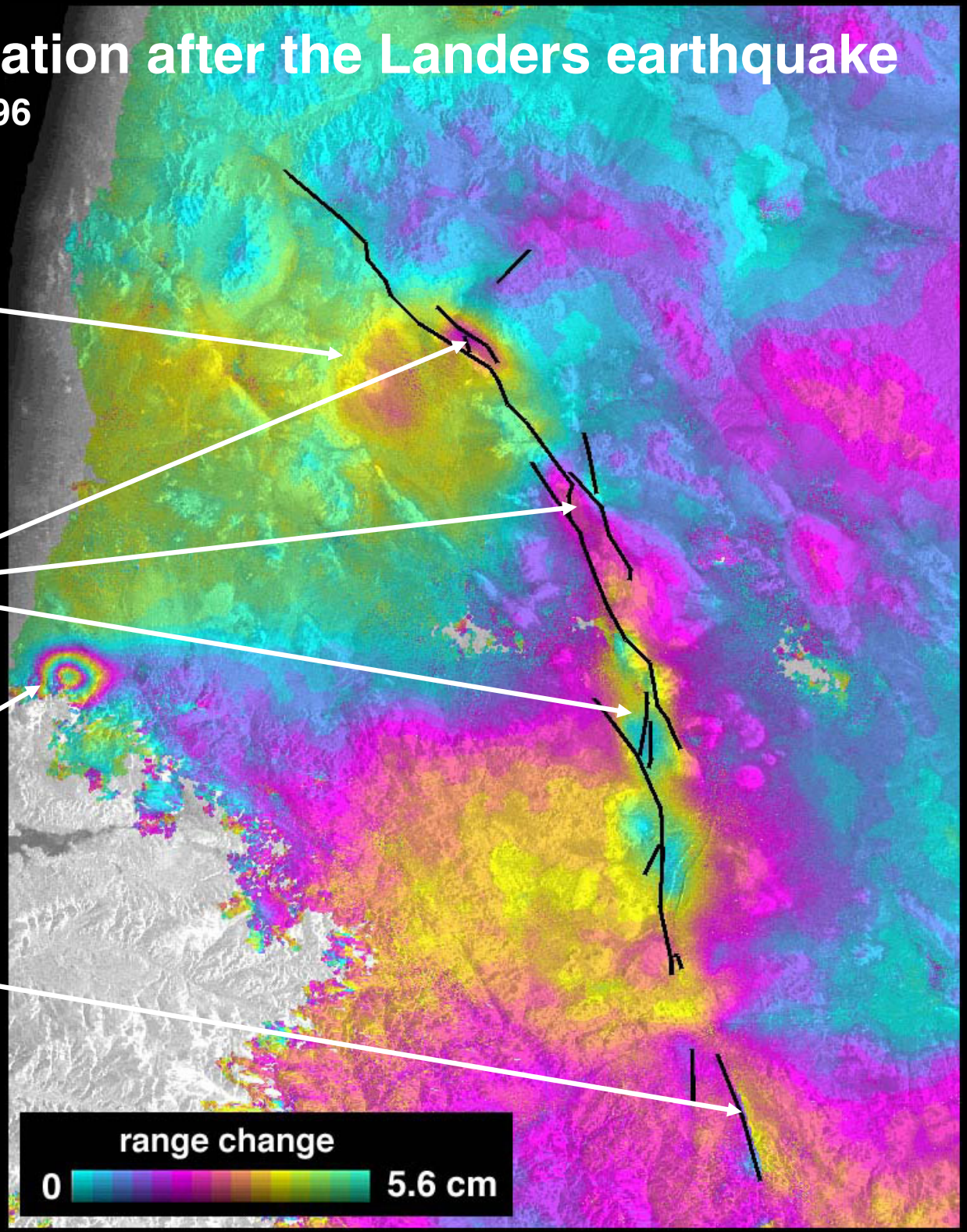
Modeled phase



Masssonnet et al., 1993

Post-seismic deformation after the Landers earthquake

ERS data: 27 Sep. 92 - 23 Jan 96

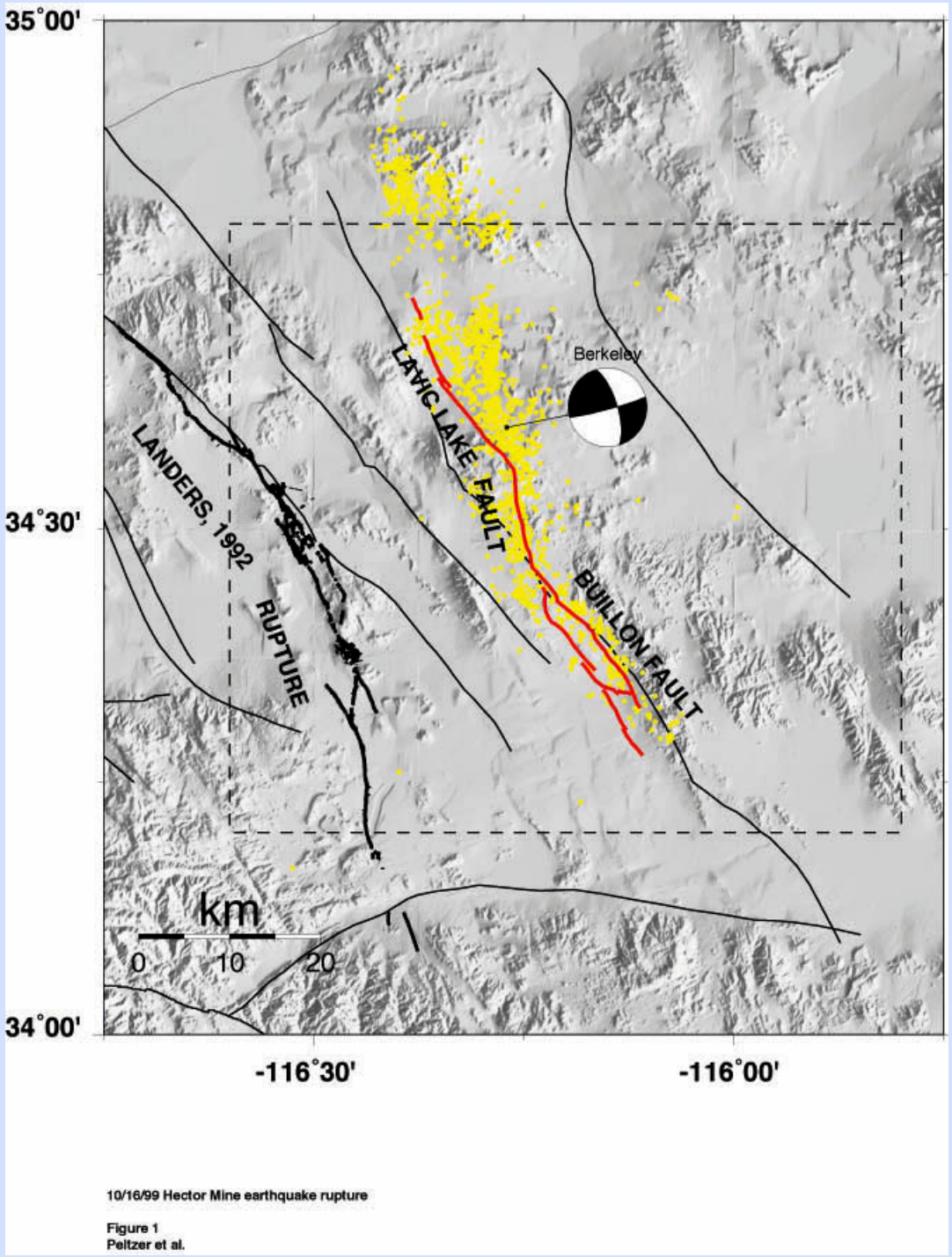


Hector Mine earthquake of October 15, 1999

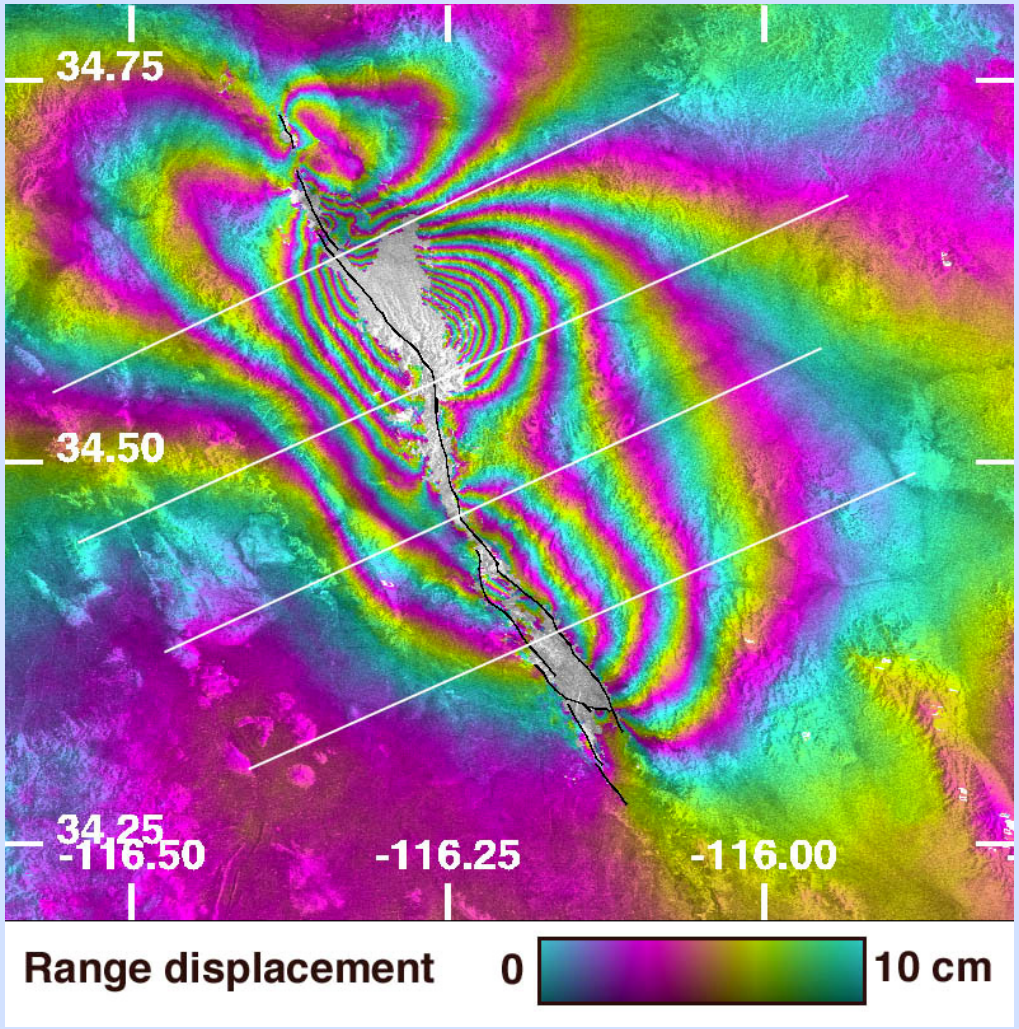
Seven years later, the eastern Mojave was the locus of another large event: The Mw7.1, Hector Mine earthquake produced a ~50 km-long surface rupture.

An ideal case for InSAR studies:

- Dry area = good phase coherence (no decorrelation)
- ERS acquisitions over one cycle, 31 days before and 4 days after the event.
- Good orbit configuration.



The Hector Mine earthquake: line of sight component of displacement



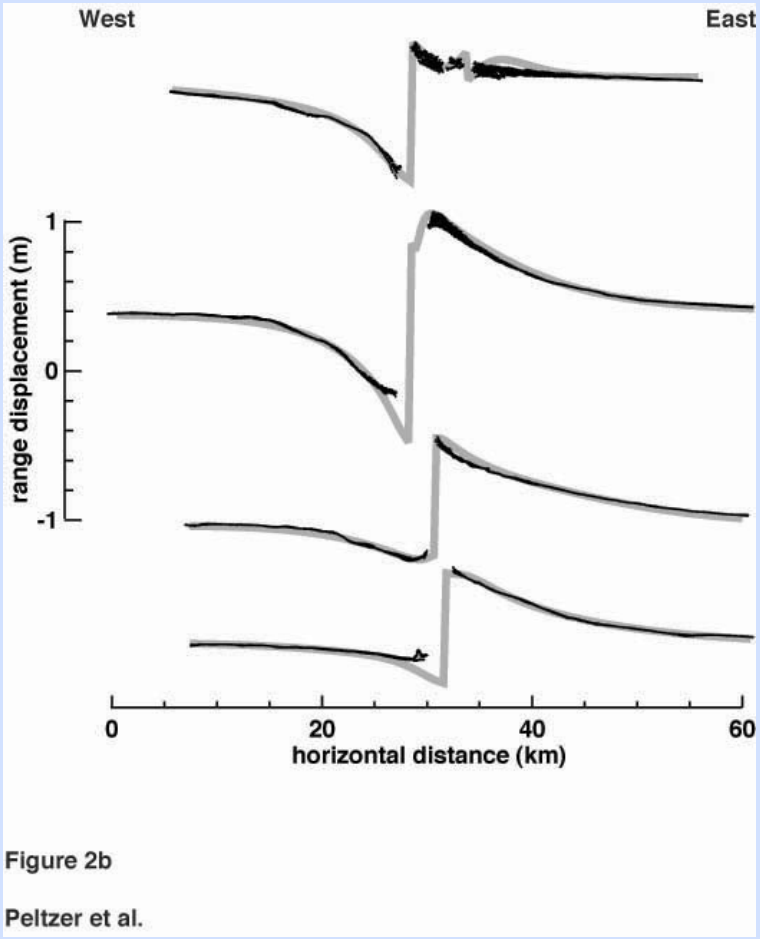


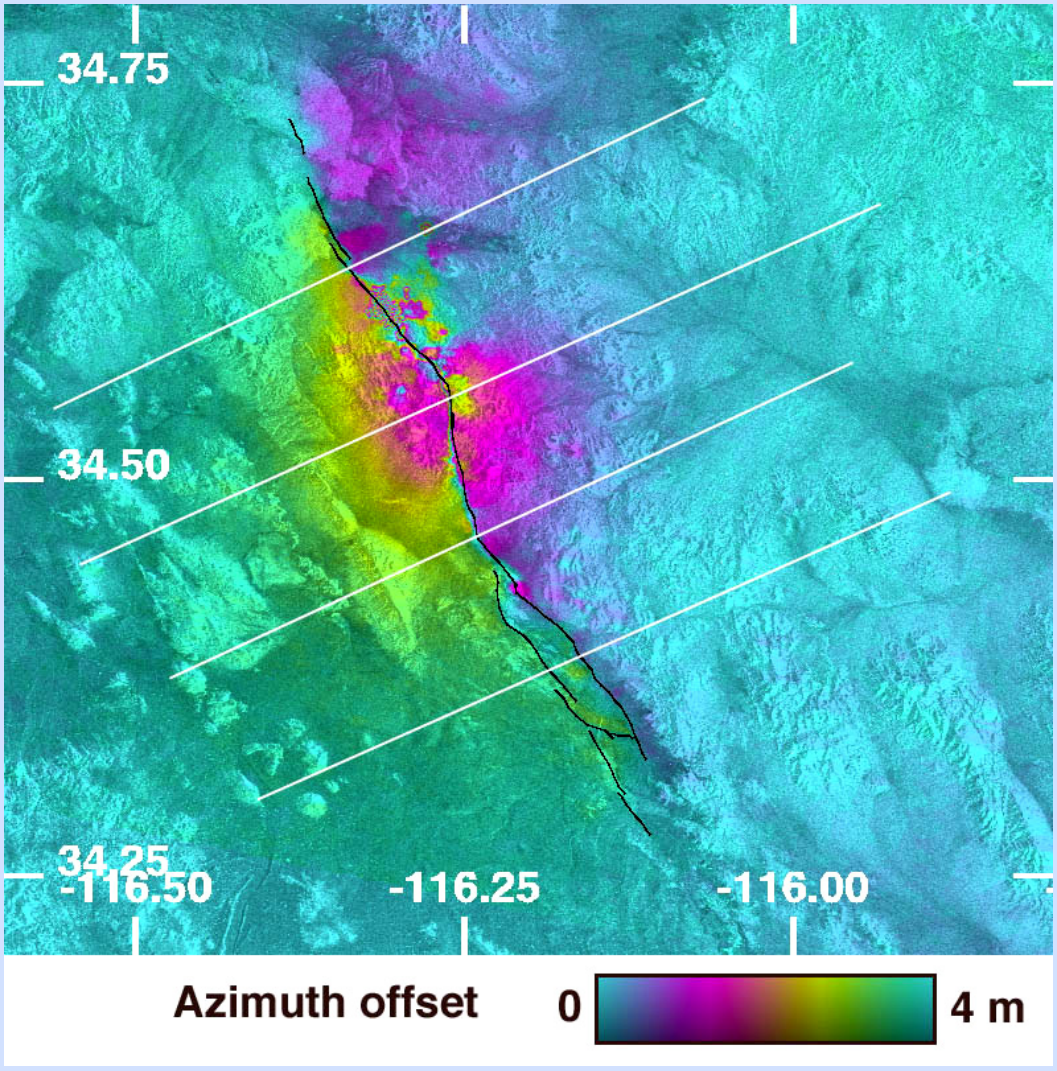
Figure 2b

Peltzer et al.

Grey areas are zones of low phase coherence

The Hector Mine earthquake: azimuth component of displacement

Azimuth offsets are obtained by correlation of amplitude image
Large ground displacement can be observed with this technique



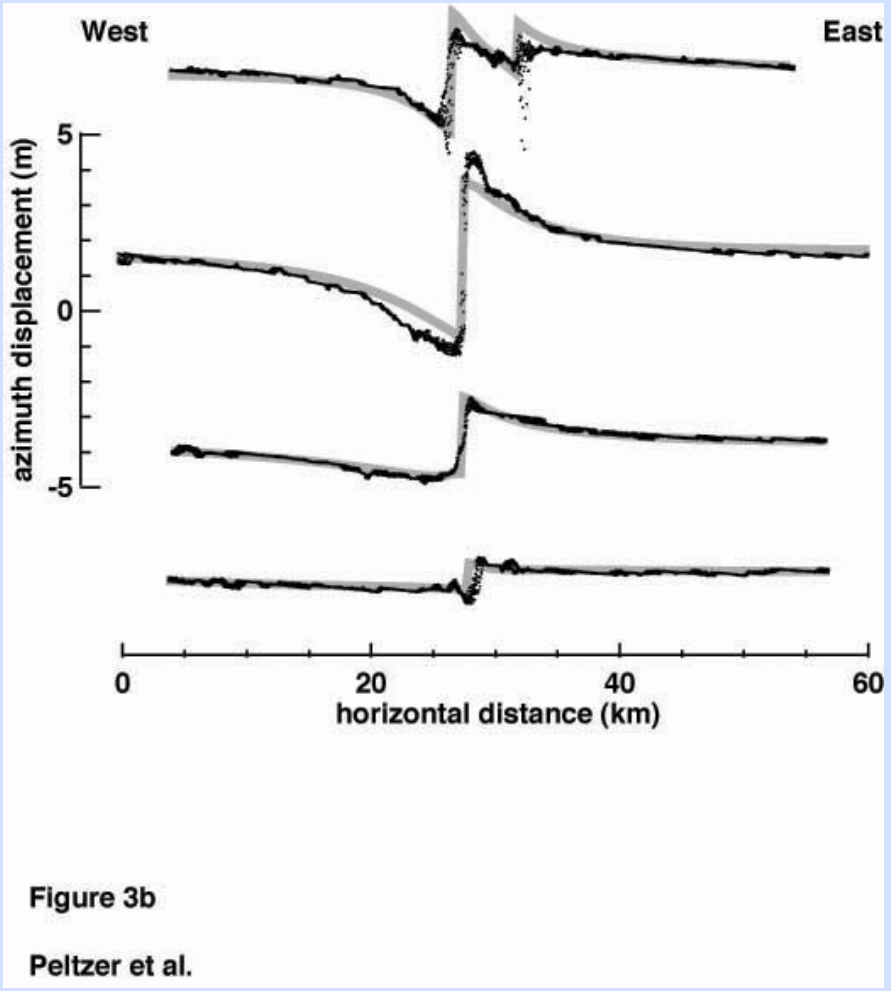
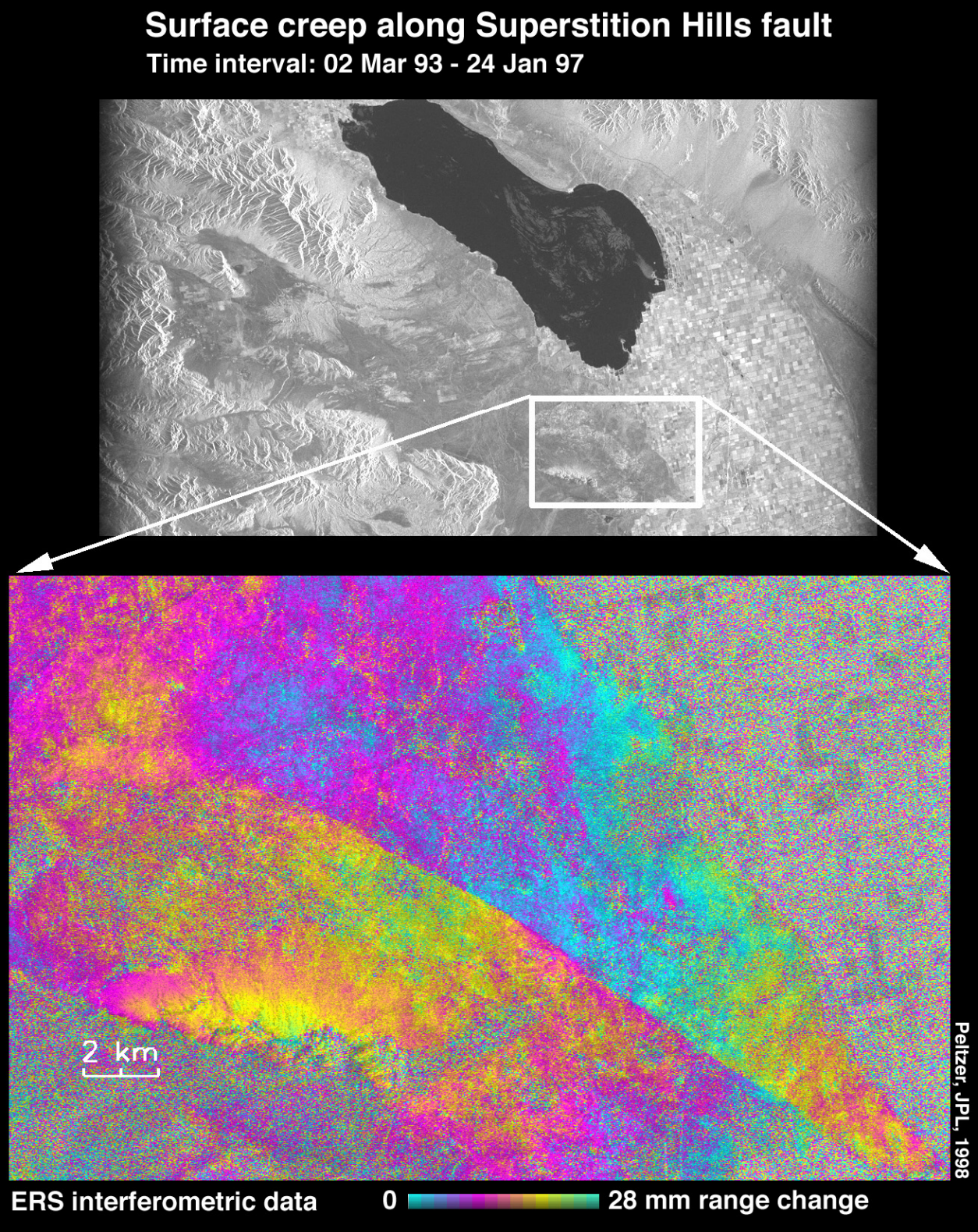


Figure 3b

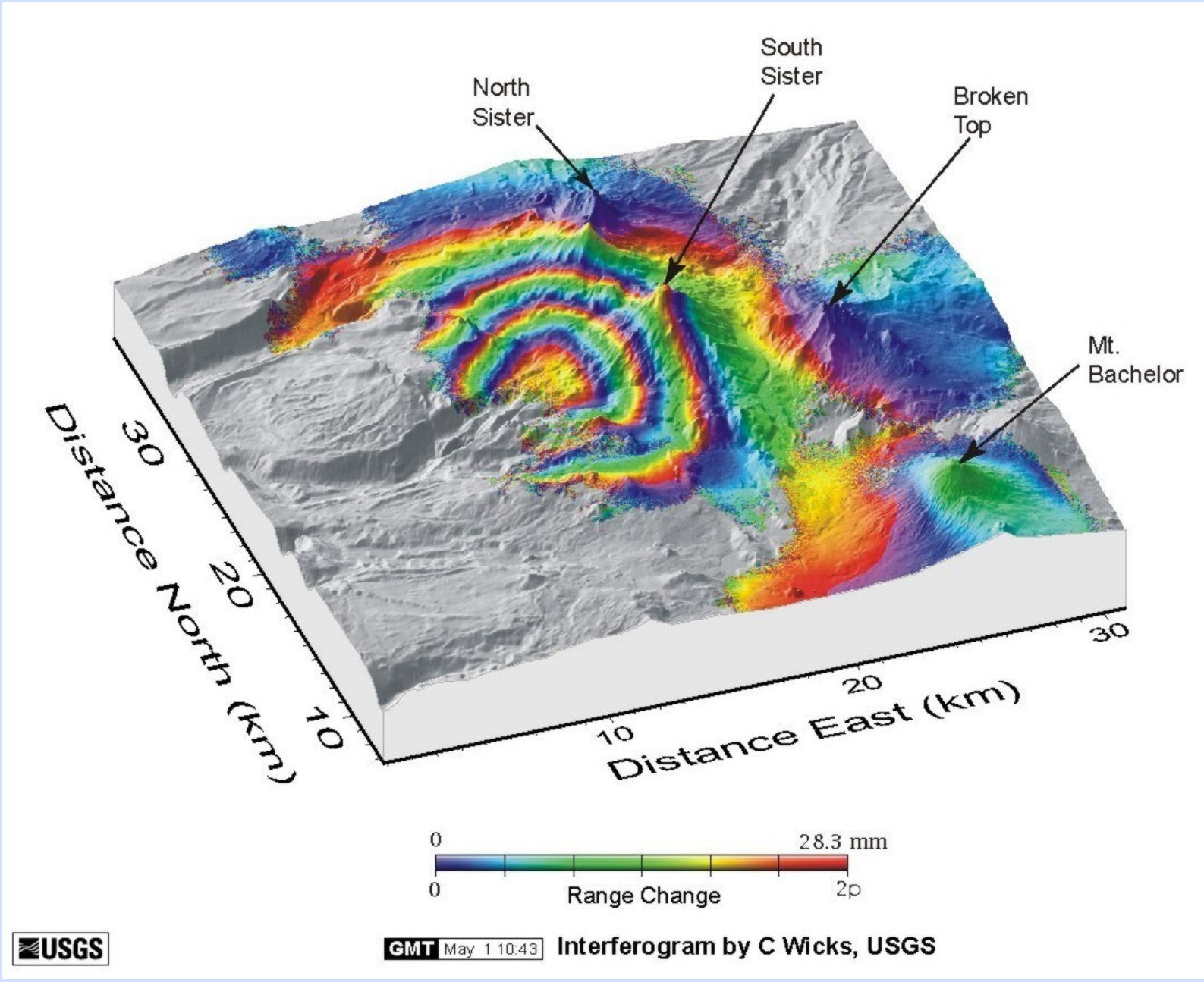
Peltzer et al.

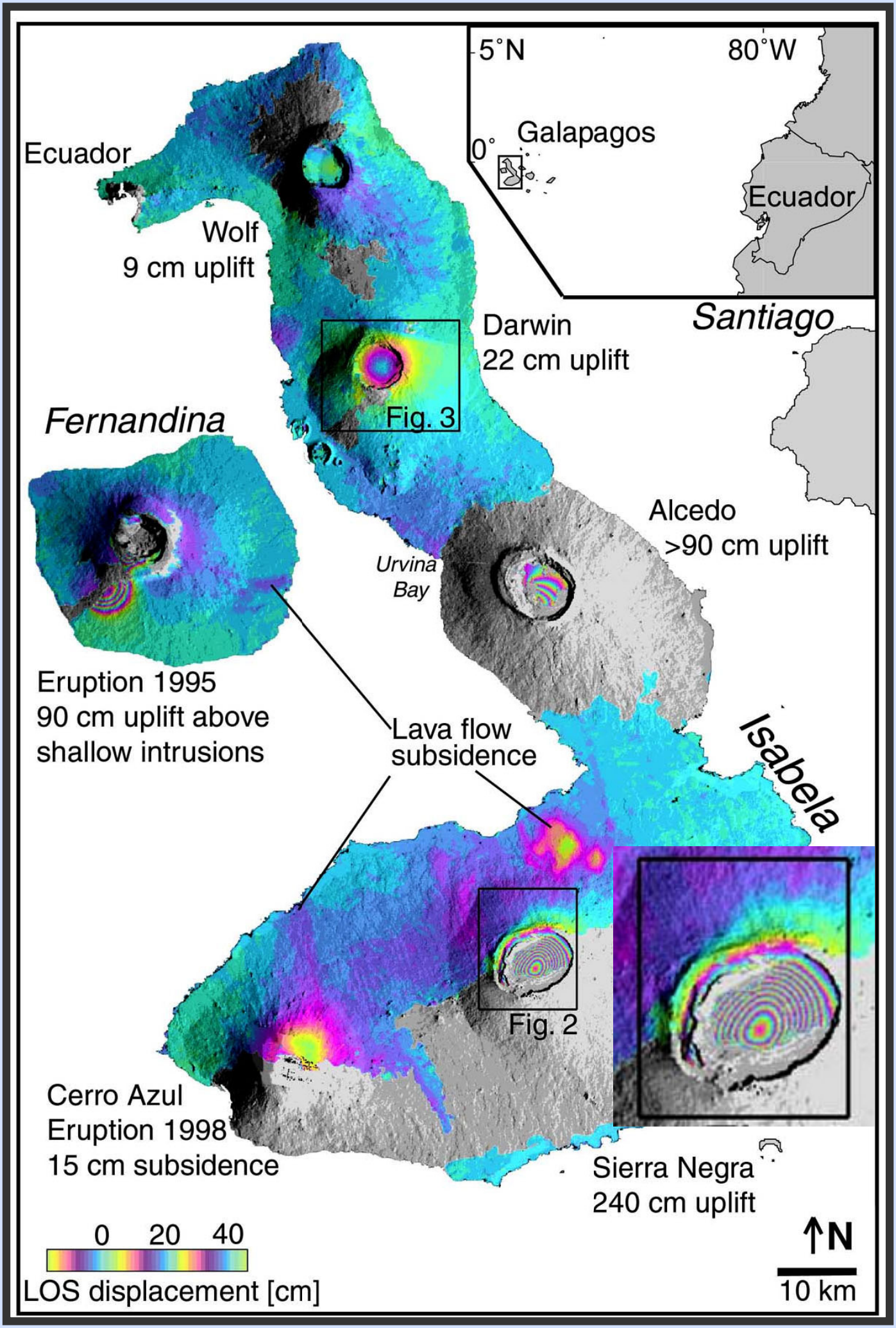
Fault creep is spectacular in interferograms


Surface creep along Superstition Hills fault
Time interval: 02 Mar 93 - 24 Jan 97
2 km
Peltzer, JPL, 1998
ERS interferometric data
0
28 mm range change

Ground Uplift near South Sister Volcano, Oregon

Up to 10 cm of uplift between August 1996 and October 2000

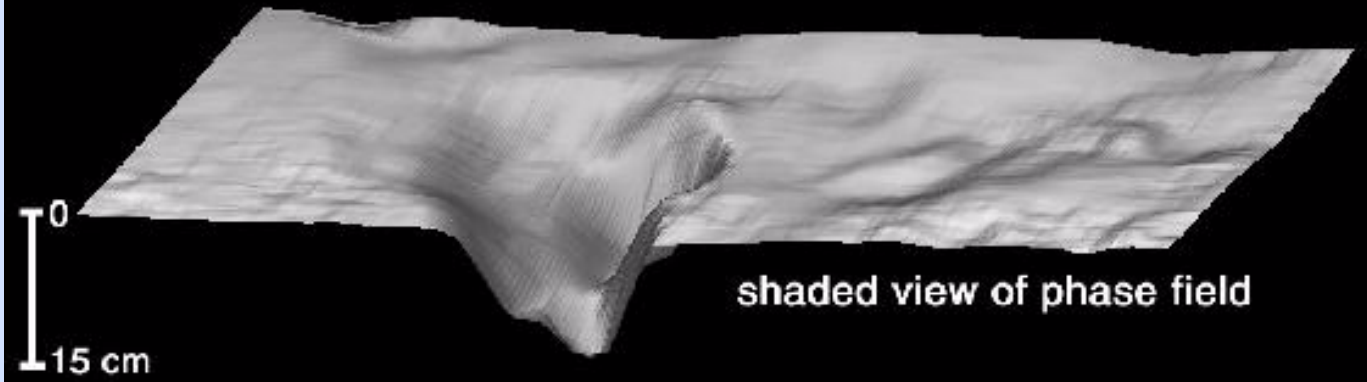



5°N
80°W
0°
Galapagos
Ecuador
Ecuador
Wolf
9 cm uplift
Darwin
22 cm uplift
Santiago
Fig. 3
Fernandina
Alcedo
>90 cm uplift
Urvina
Bay
Eruption 1995
90 cm uplift above
shallow intrusions
Lava flow
subsidence
Isabela
Fig. 2
Cerro Azul
Eruption 1998
15 cm subsidence
Sierra Negra
240 cm uplift
0 20 40
LOS displacement [cm]
N
10 km

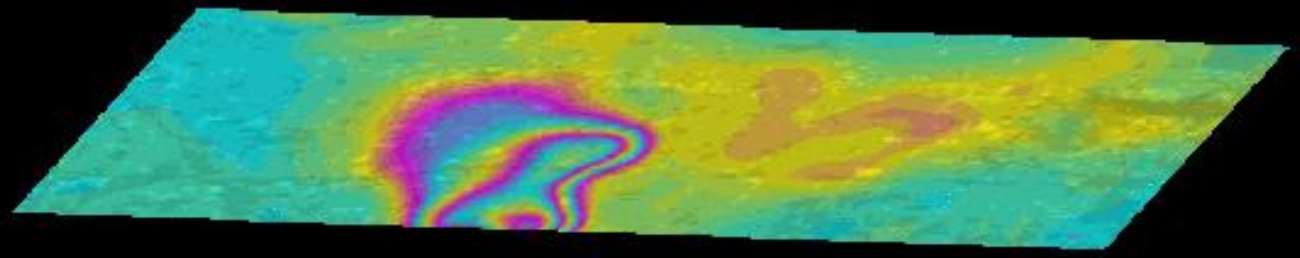
Ground subsidence near Pomona, California

Time interval: 20 Oct 93 - 22 Dec 95

distorted AAA street map



shaded view of phase field

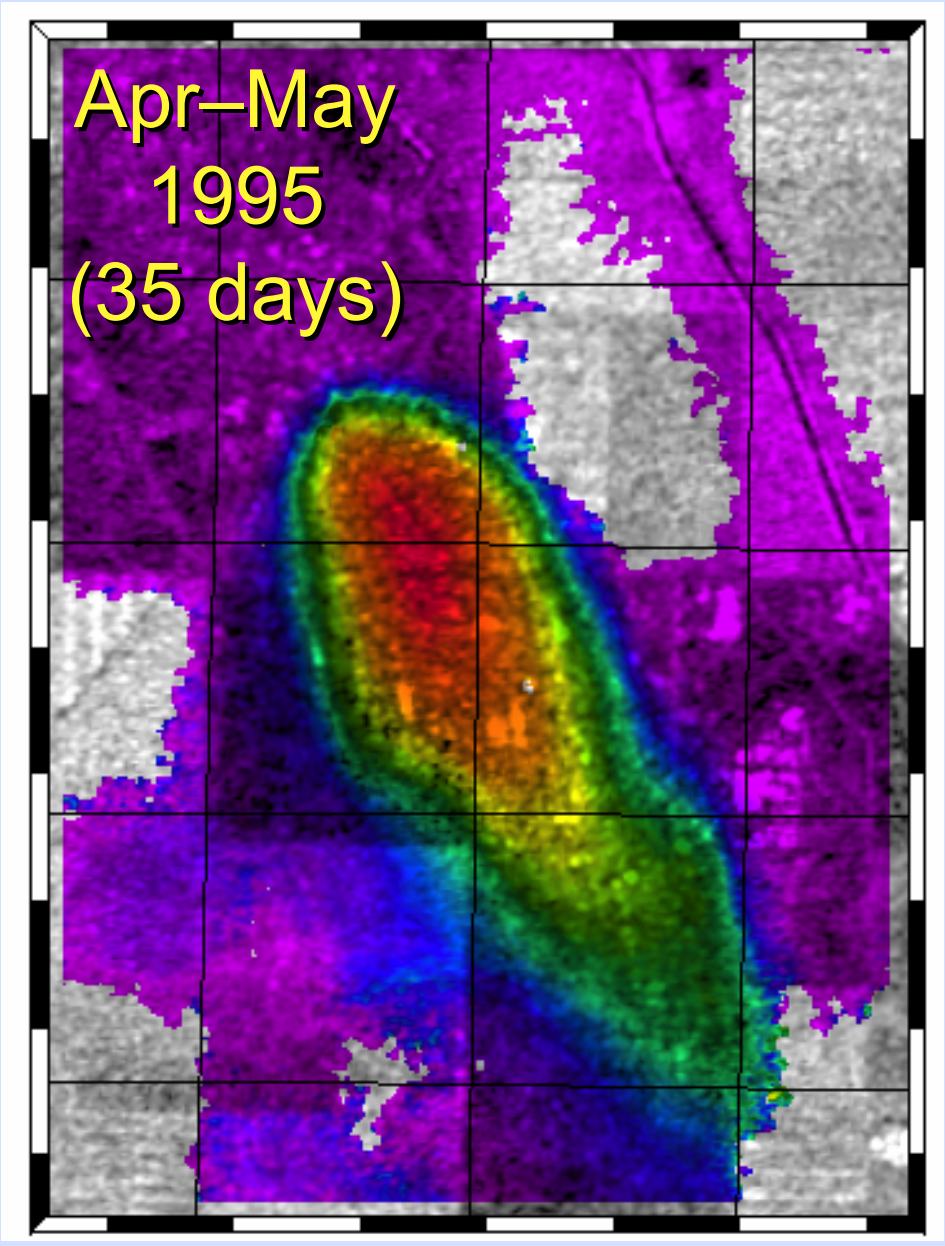


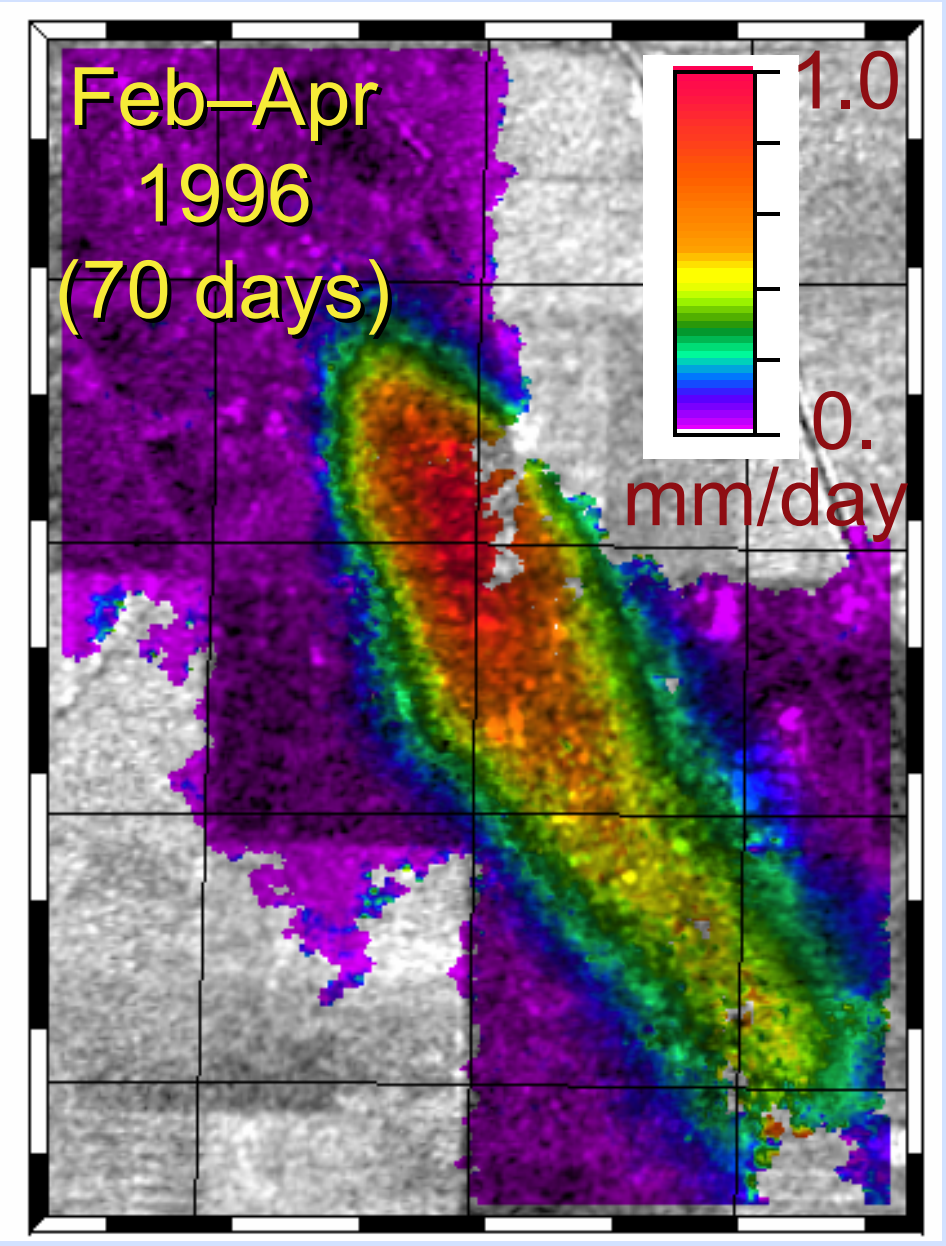
ERS-1, 3-pass interferogram

G. Peltzer, 1997 - JPL

SAR interferometry—ERS

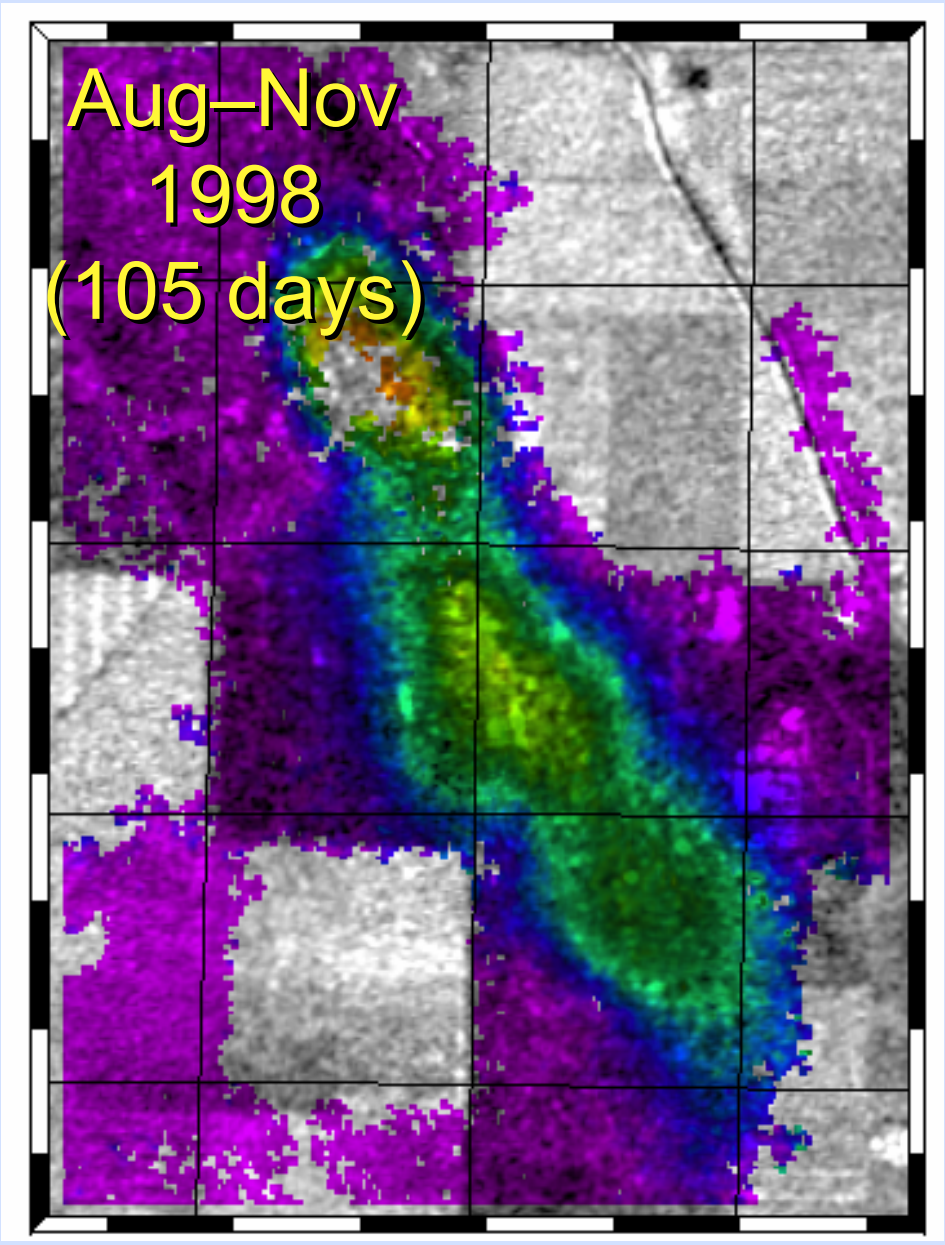
Lost Hills subsidence rates were fast in 1995–1996

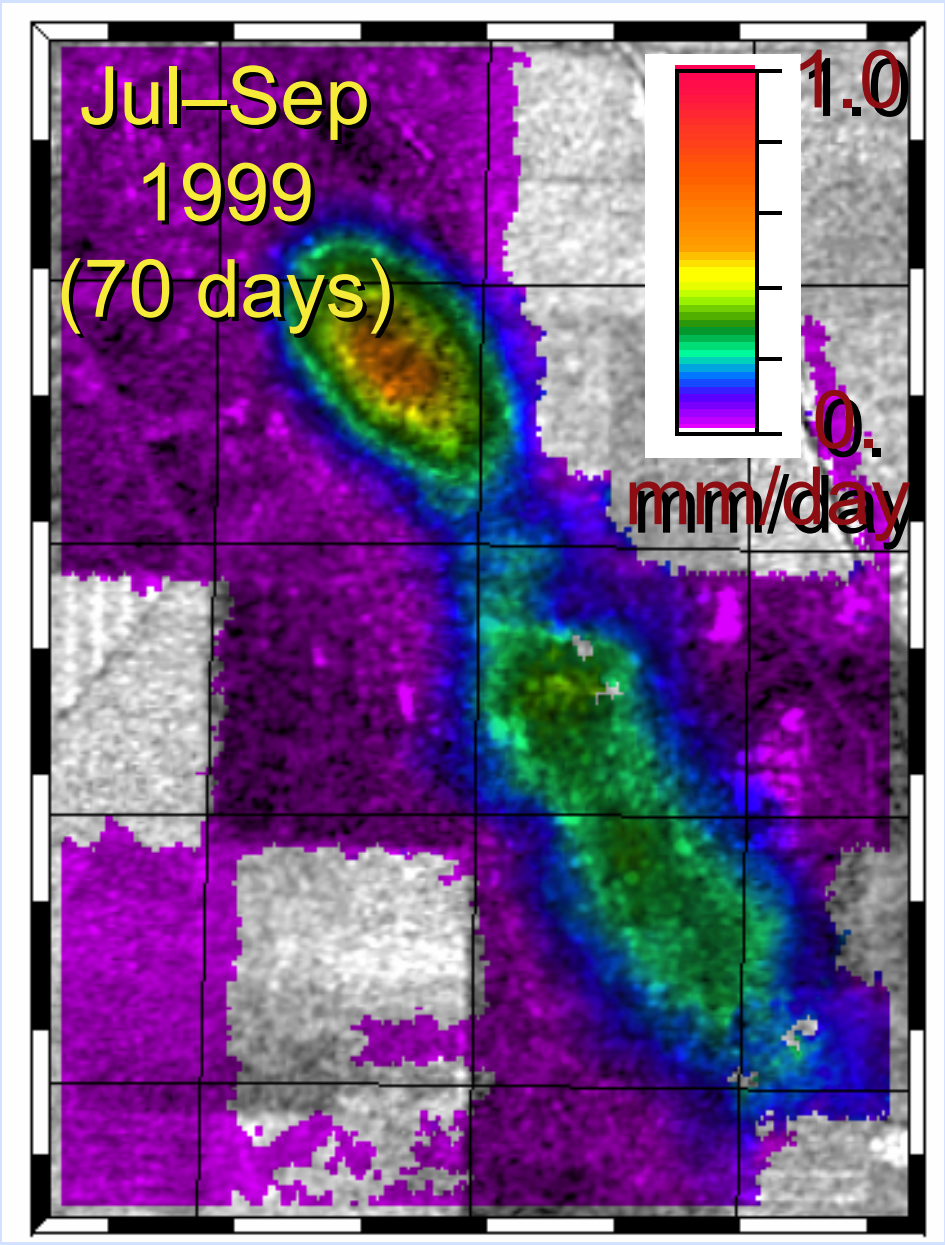




SAR interferometry—ERS

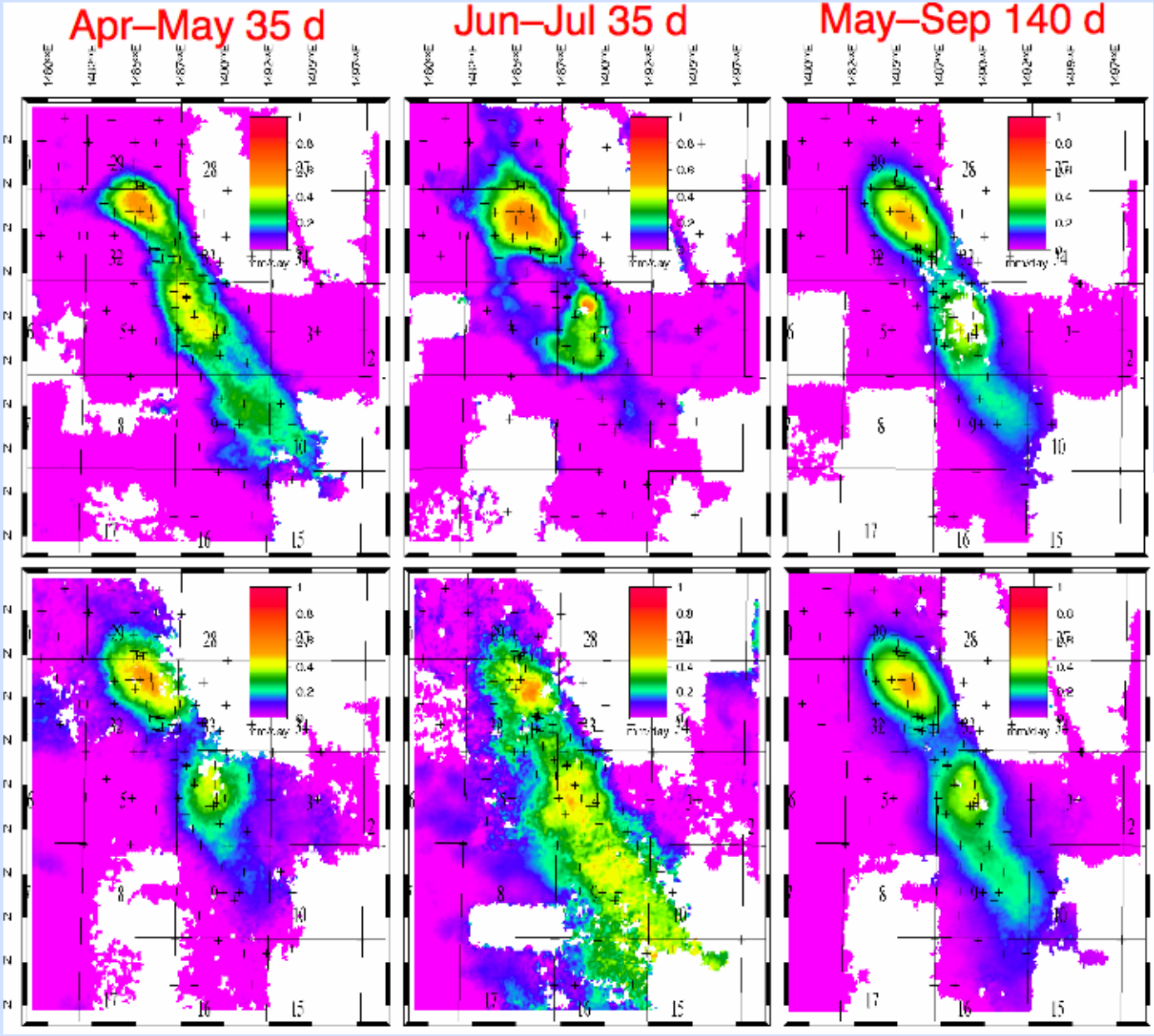
rates decreased in 1998–1999





InSAR errors—atmosphere

ERS interf. from 2000



Li, Z., J.-P. Muller, P. Cross, and E.J. Fielding, Interferometric synthetic aperture radar atmospheric correction: GPS, Moderate Resolution Imaging Spectroradiometer (MODIS), and InSAR integration, Journal of Geophysical Research, 110 (B3), B03410

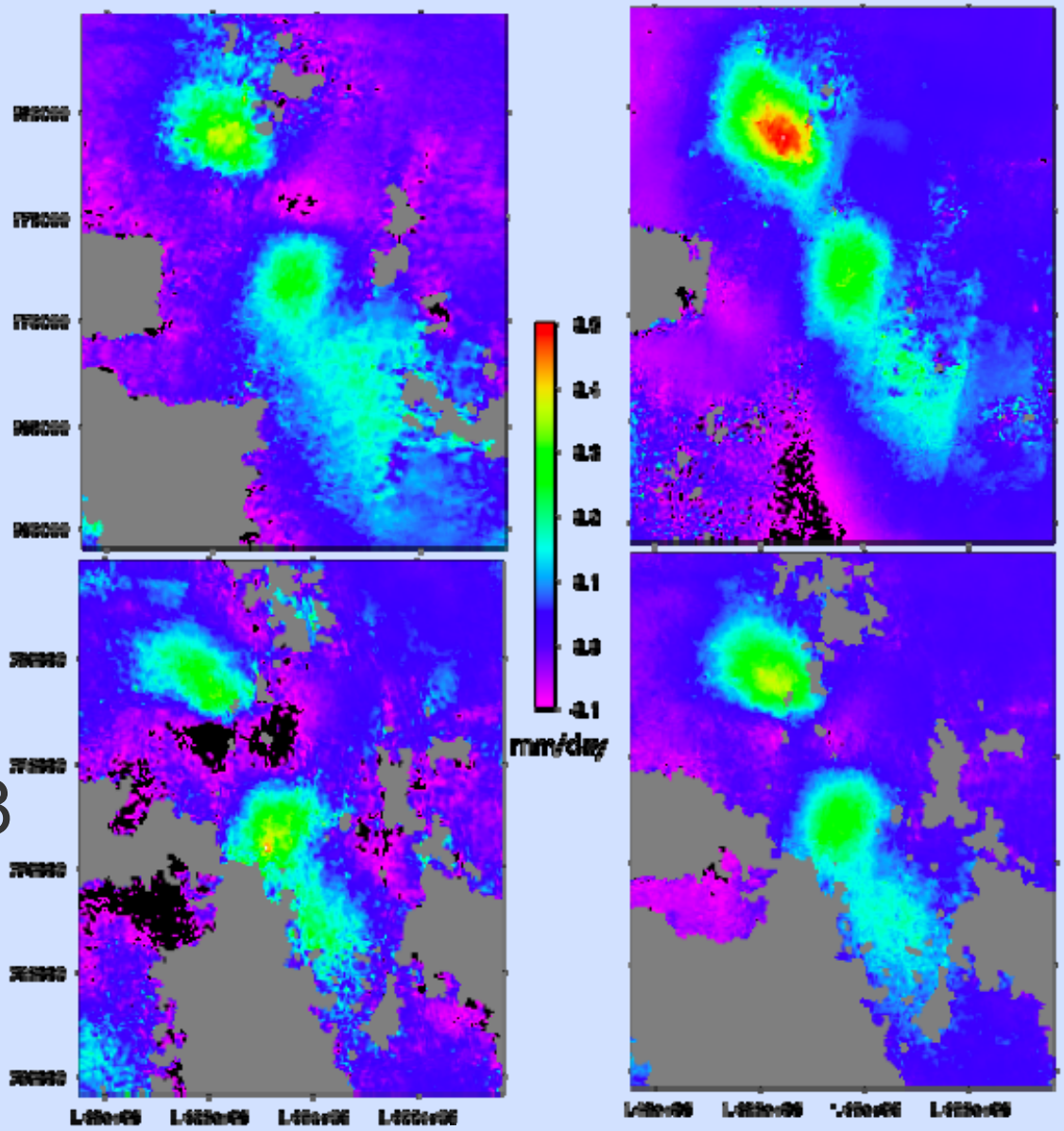
Increasing temporal resolution

- Radarsat-1 and Envisat have multiple beams
- Can image same location more than once per repeat cycle
- More interferograms in shorter time interval
- Complication is different incidence angles
- More frequent coverage needed for input to oilfield operations

three overlapping 48-day Radarsat-1 interf.

Early September to mid-October 2002

9/3–10/21
S1d



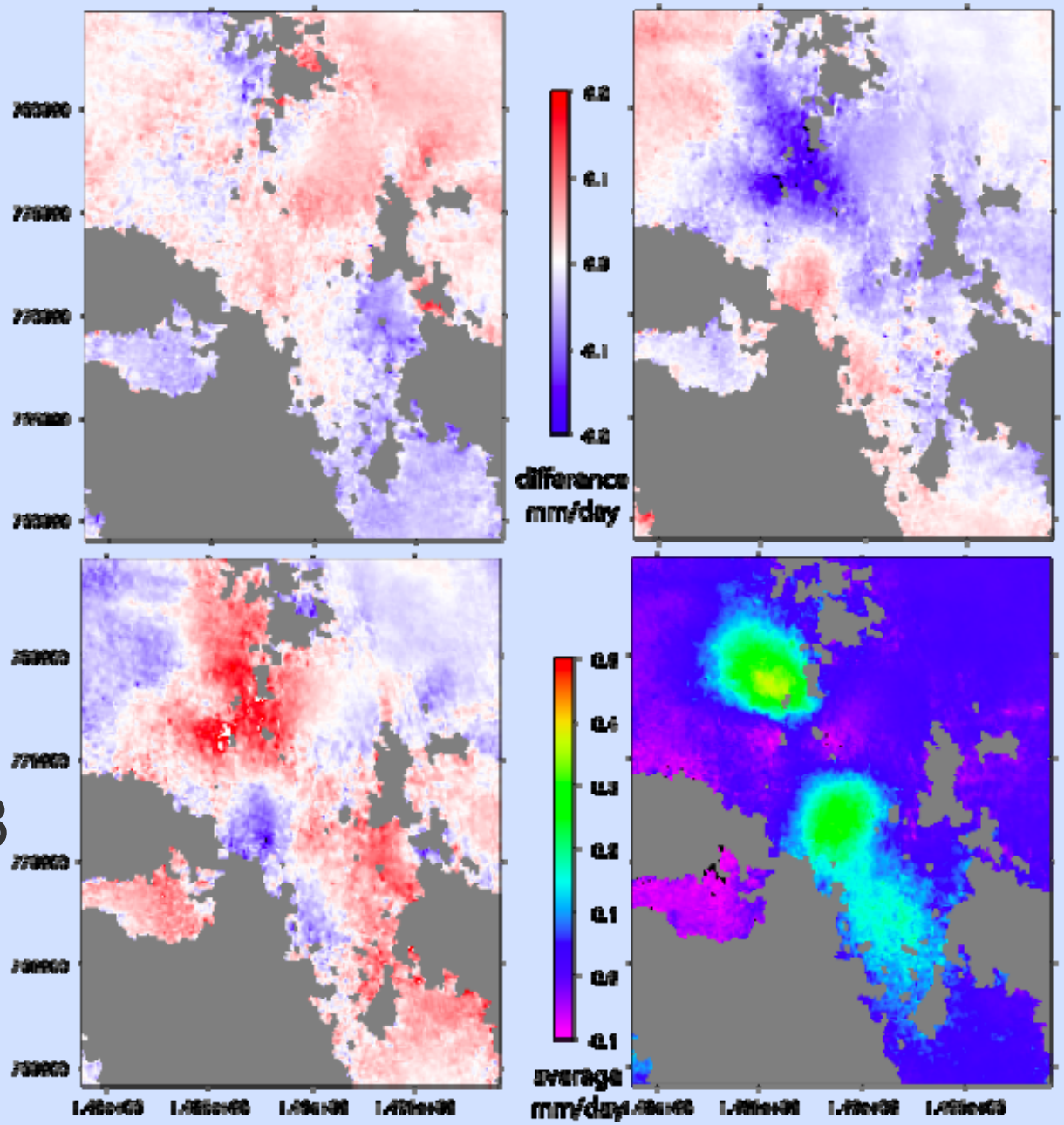
8/31–10/18
F1d

9/10–10/28
S2a

average of three

Estimating atmospheric errors—differences from average

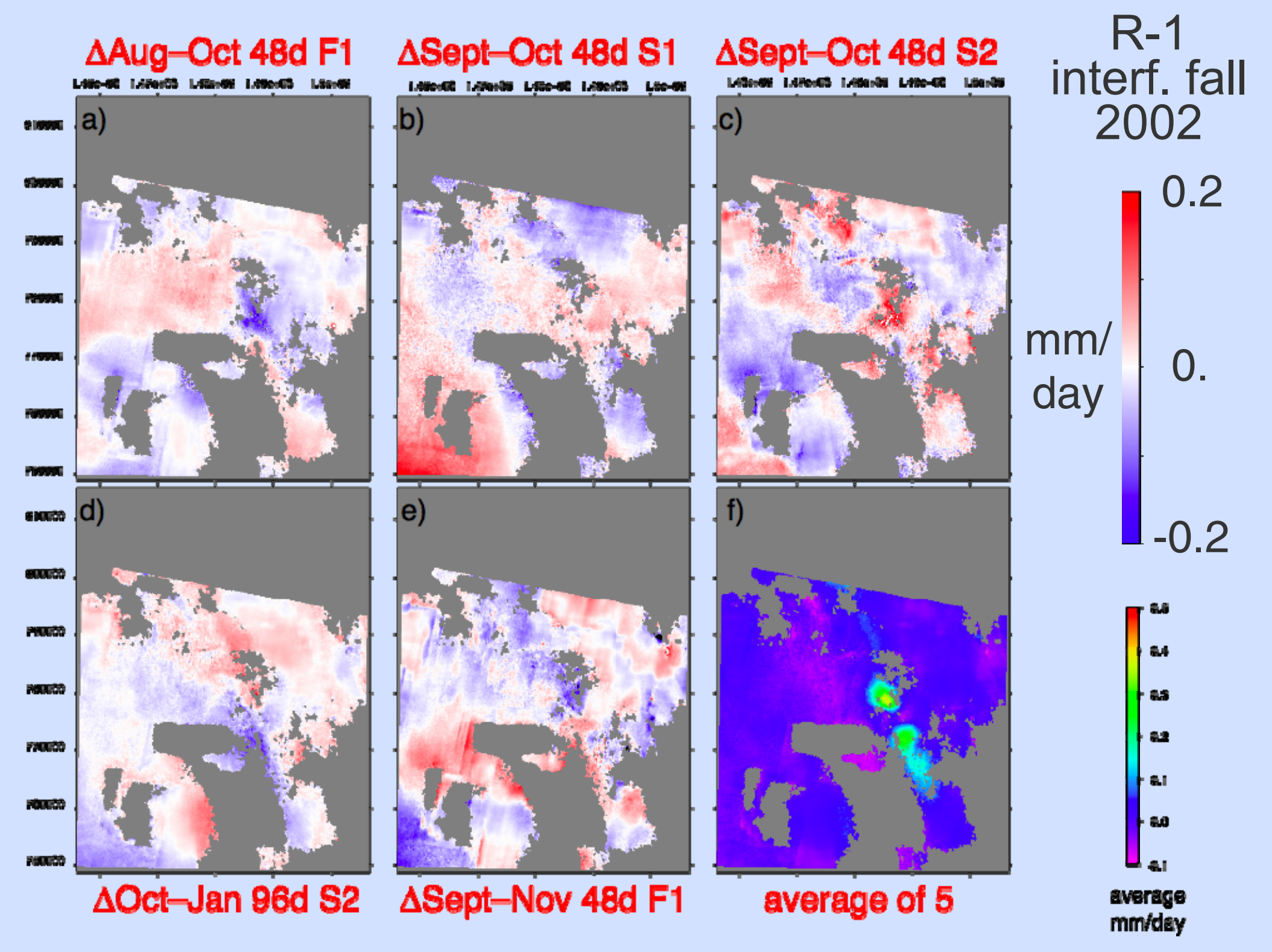
difference 9/3–10/21 S1d



difference 8/31–10/18 F1d

difference 9/10–10/28 S2a

average of three

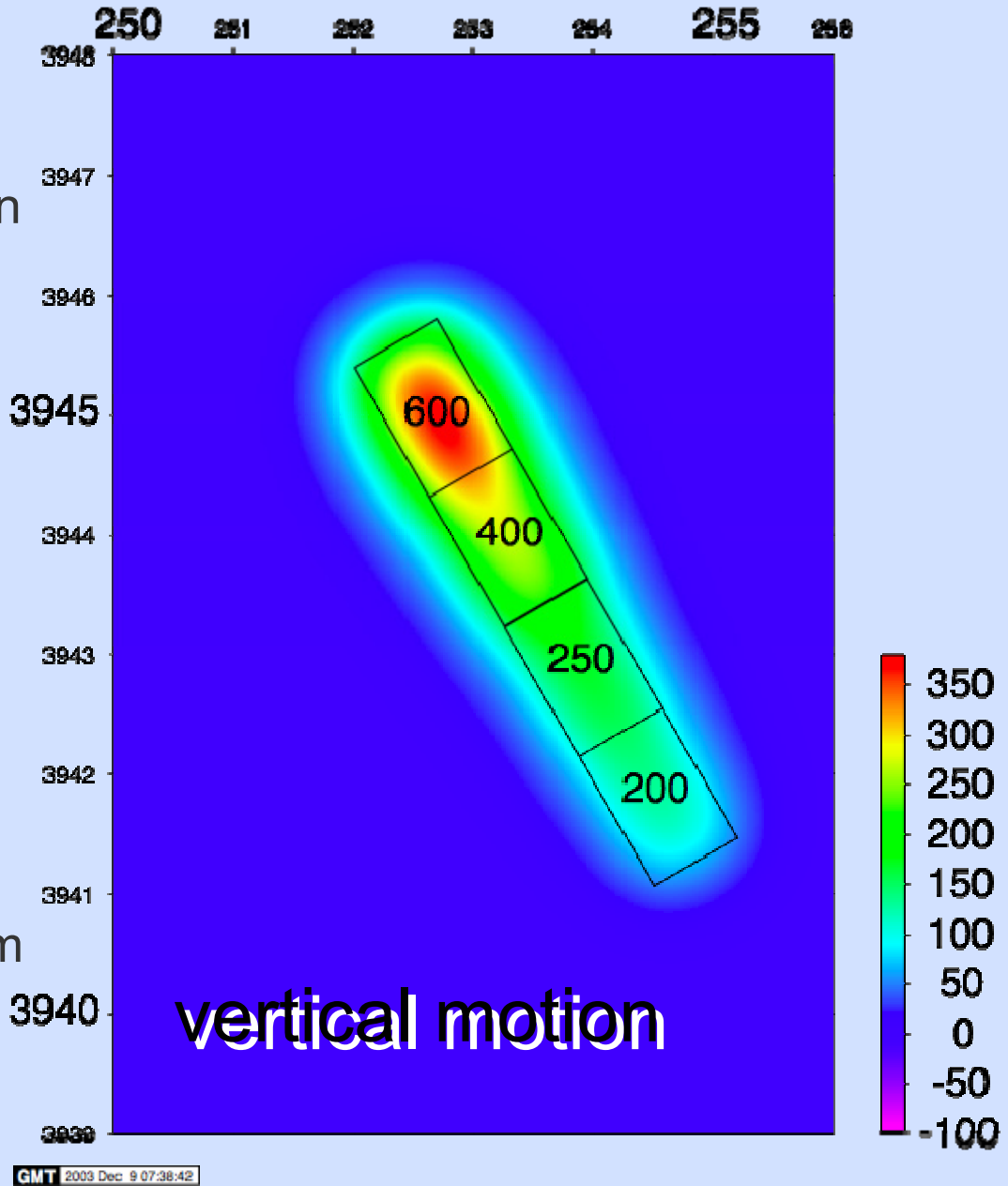

ΔAug–Oct 48d F1
ΔSept–Oct 48d S1
ΔSept–Oct 48d S2
R-1
interf. fall
2002
a)
b)
c)
d)
e)
f)
0.2
mm/
day
0.
-0.2
ΔOct–Jan 96d S2
ΔSept–Nov 48d F1
average of 5
average
mm/day

Radarsat-1 beam modes used

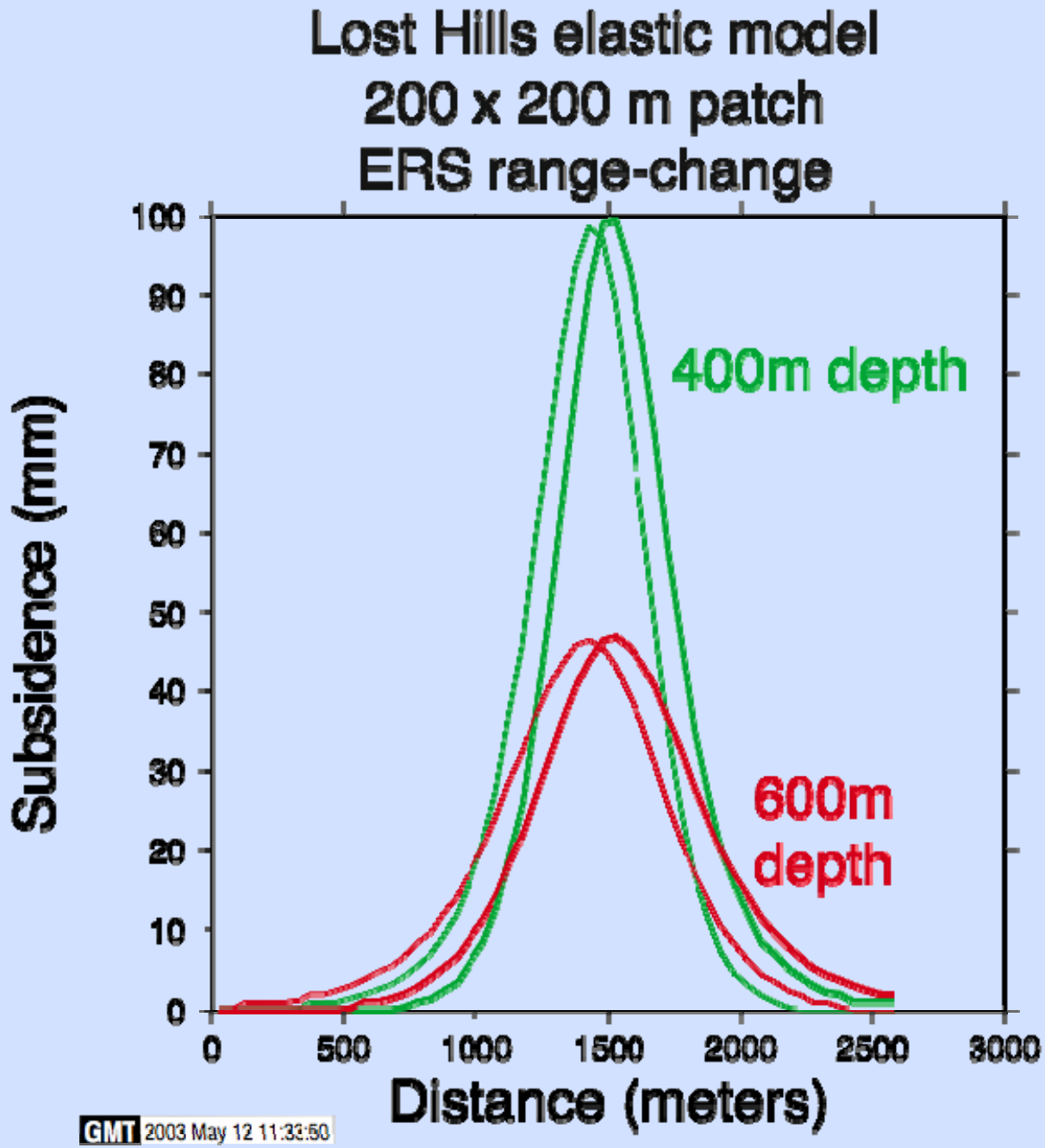
beam mode	incidence angle (deg.)	V: cosine (inc. ang.)	H: sine (inc. ang.)
S1	23.21	0.919	0.394
S2	27.7	0.885	0.465
F1	38.4	0.784	0.621
F2	40.68	0.758	0.652
F3	42.75	0.734	0.679
F4	44.72	0.711	0.704

Elastic half-space model to relate radar observations to reservoir behavior Okada equations

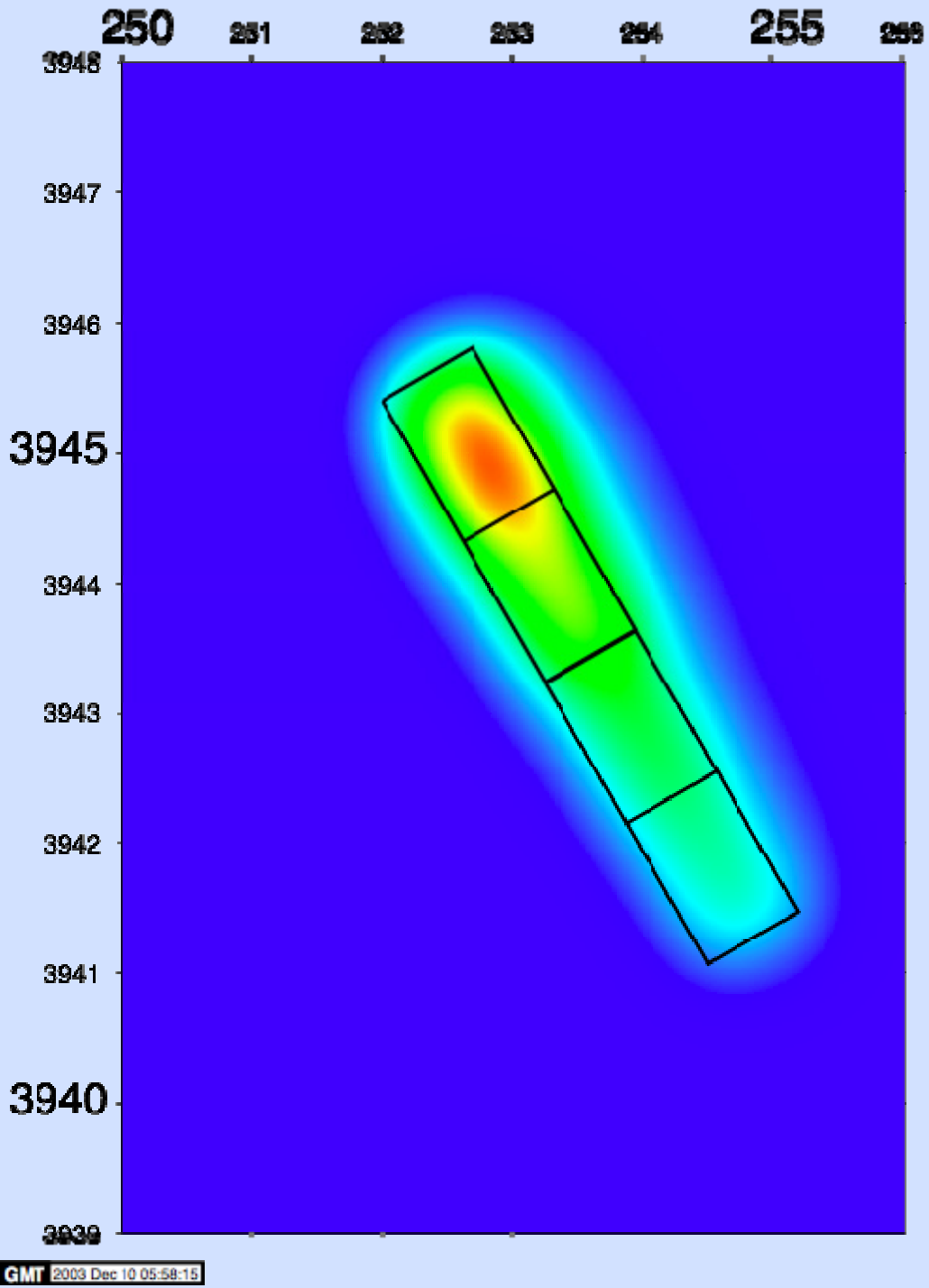
- Feigl and Dupré 1999 implementation
- linear elastic half-space
- rectangular patches 800 x 1250 m
- constant tensile dislocation—compaction amount shown
- depth 600 m
- maximum vertical subsidence 372mm over patch with 600m depth



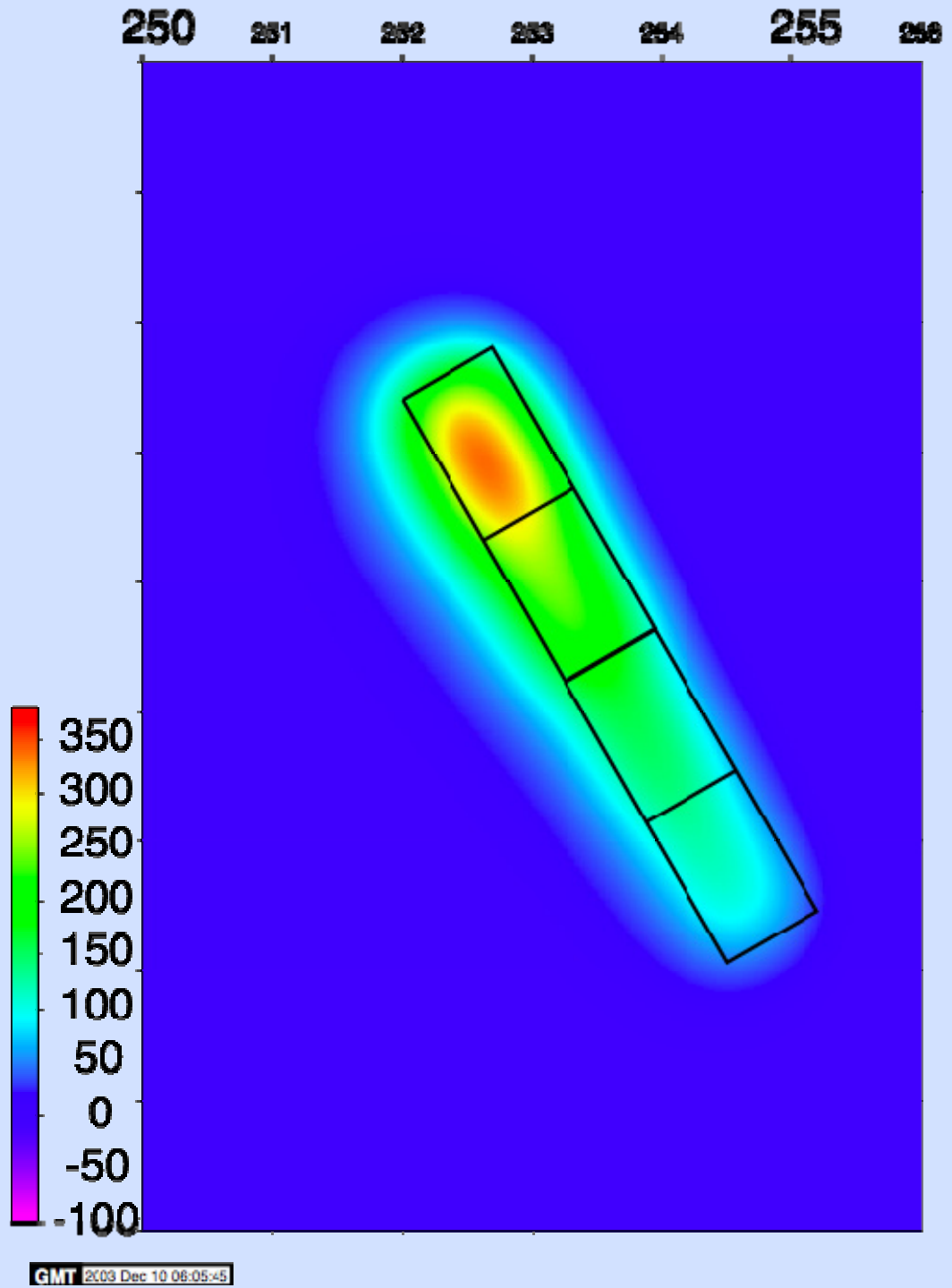
- ERS 23-degree incidence angle
- Okada planar dislocation 200 x 200 m
- 1000 mm of compaction at depth
- much less at surface



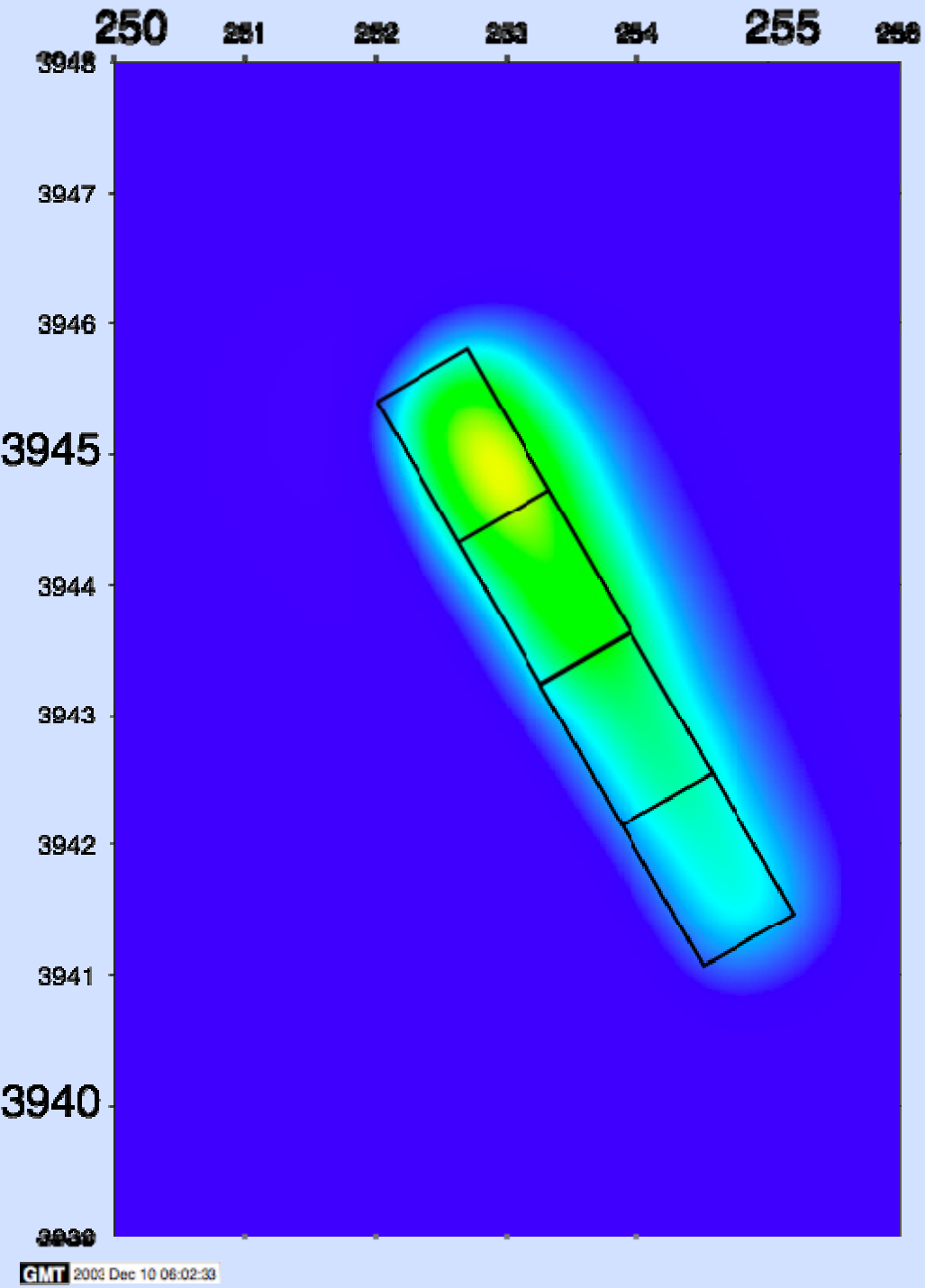
R-1 beam S1d

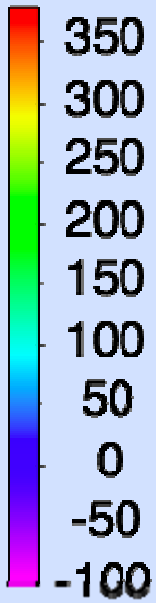


R-1 beam S2a ~=ERS asc.

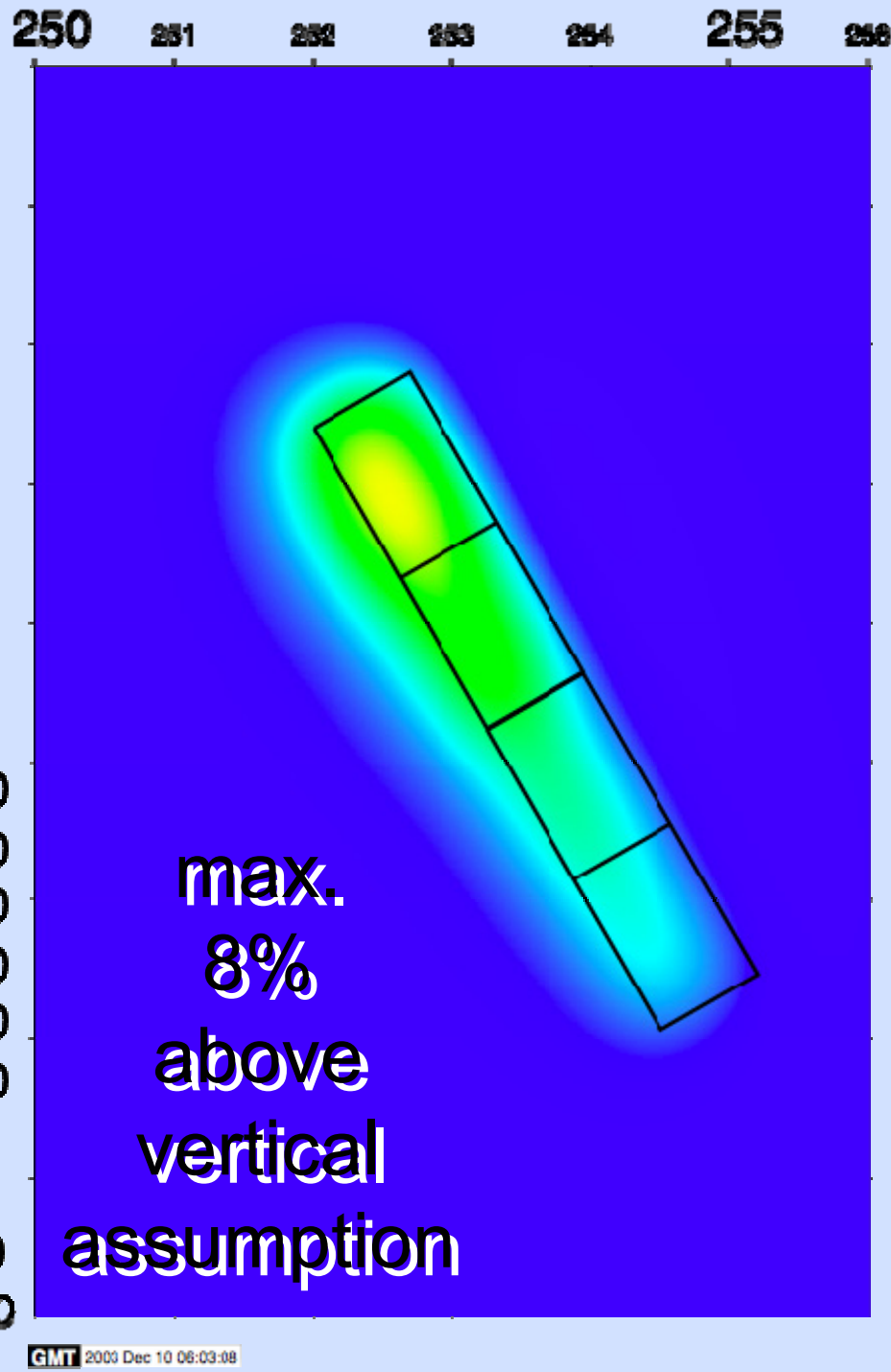


R-1 beam F3d





R-1 beam F4a



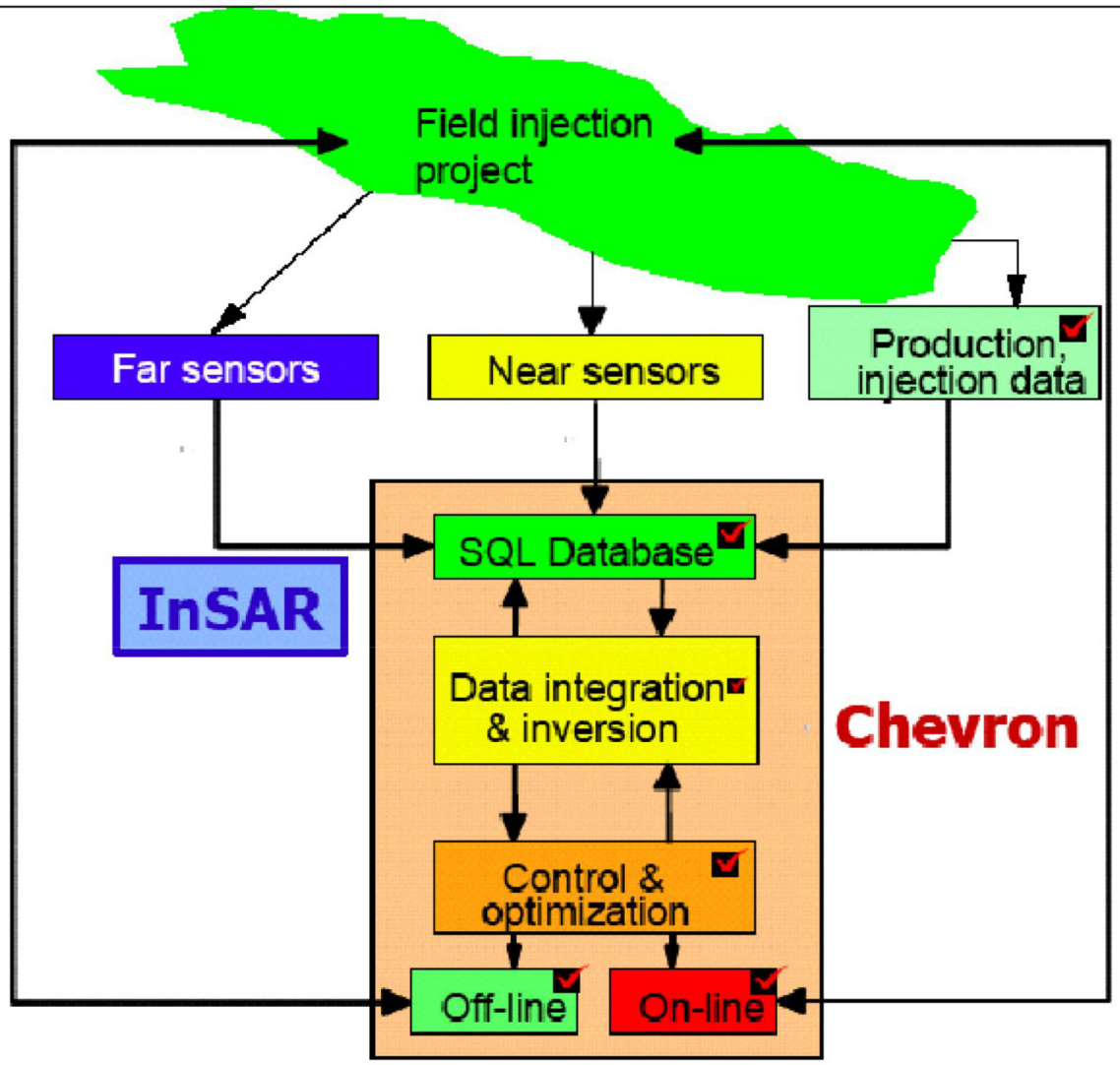


Fig. 3 - The proposed field wide system of surveillance and control. This paper will focus on the InSAR imaging of the field surface and the use of production/injection data. The controller system has been described elsewhere[2,6,19] and is being implemented by Chevron at Lost Hills.

Figure 20. Automated injection header

DISASTER MANAGEMENT

PFA: DOE

SCIENCE MODELS

UCB, LCB
FLUID FLOW

JPL

INTEROPERABILITY

SUBSIDENCE CHANGE

Data

MEASUREMENTS / MONITORING

GPS

INSAR (AIRSAR)

LIDAR (ATM)
GeoSar

RADARSAT
ERS
ENVISAT

ALOS PALSAR

TOPOGRAPHY

PST

SUBSIDENCE MONITORING

DOE / CHEVRON

UC BERKLEY
and
LAWRENCE
BERKLEY

MODELING and CONTROL SYSTEM

CHEVRON

OIL FIELD OPERATIONS

Socio-Economic Benefits:

$100M NRC, 1991

Fielding, Eric
Blom, Ron

$317 K – NASA
$50 K - Chevron

Technology Transfer

- Original goal to demonstrate utility of InSAR for oil field subsidence monitoring, set a path to developing an operational capability, is achieved.
- Model incorporating InSAR data for water injection and control of wells is in development-space technology developed by NASA will likely be used for oil field operations.
- InSAR data processing now handed off to a commercial company, Atlantis Scientific, NASA/JPL have done our job!
- Successful project going from concept>research>validation, field trails for implementation in progress. Major component to success was user involvement from very beginning.
- Two key publications in Society of Petroleum Engineers.
- Use of Satellite Radar Images in Surveillance and Control of Two Giant Oilfields in California, Patzek, T., et. al., SPE 71610.
- Lost Hills Field Trial-Incorporating New Technology for Reservoir Management, Brink, J.L., et. al., SPE 77646.

Conclusions for Lost Hills

- **Semiannual GPS surveys provide long time series showing total subsidence > 2m.**
- **ERS InSAR shows subsidence rates dropped from max. 1.1 mm/day in 1995-1996 to 0.4 mm/day in 1998-2000.**
- **Interaction between fluid injection and subsidence/compaction much more complicated than expected.**
- **InSAR provides critical data, geographically comprehensive measurements of surface deformation.**
- **Radarsat-1 and Envisat now provide more frequent coverage, key to quasi operational implementation.**
- **Effective combination of multiple data sources requires use of geophysical model for oil field operations. Space technology is a tool, not a magic bullet.**

InSAR Potential Satellites

Satellite	Launch	End	Wavelength
Seasat	1978	1978	L
SIR-B	1984	1984	L
ERS-1	**1991**	**2000**	**C**
JERS-1	1992	1998	L
SIR-C	1994	1994	L,C,X
ERS-2	**1995**		**C**
Radarsat-1	**1995**		**C**
SRTM	2001	2001	C,X
Envisat	**2002**		C
Radarsat-2	2005		C
ALOS	2005?		L
NASA L-Band someday			***L***

Radar Data Sources

Eurimage	ERS-1, ERS-2, Envisat	www.eurimage.com/
Radarsat International	Radarsat	www.rsi.ca
NASDA	JERS-1, ALOS	www.eoc.nasda.go.jp/catalogue/catalogue_e.html
USGS/NASAEDC	SIR-C (images), SRTM (topo and images)	edcdaac.usgs.gov/dataproducts.html
JPL/AIRSAR	*AIRSAR-P,L,C band Polarimetry and InSAR (topo only)*	*http://airsar.jpl.nasa.gov/*
GeoSAR	*Airborne P and X band Polarimetry and InSAR (topo only)*	*http://www.geosar.com/*

InSAR Processing and Software

ROI_pac	JPL/Caltech	Research	Unsupported	Contact Jennifer Schlickbernd @ JPL 818 354-2241
EarthView	Atlantis Scientific	Commercial	Supported & Consulting available	www.atlsci.com/
DIAPASON	CNES	Research/ Commercial	Training,support available	www.empreses.net/altamira/
GAMMA	GAMMA Remote Sensing	Commercial	Supported, consulting available	www.gamma-rs.ch/
3DSAR	Vexcel	Commercial	Supported & consulting	www.vexcel.com/radar/3dsar.html